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THESIS

ANALYSIS OF SHIELDED SUSPENDED
STRIPLINE
DISCONTINUITIES

by

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Analysis of Shielded Suspended Stripline Discontinuities

by

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ABSTRACT

An evaluation of the shielded suspended stripline was conducted using an X-band waveguide to isolate a suspended strip transmission line. The analysis was conducted below the functional cutoff frequency of the X-band waveguide over a wide range of frequencies. The scattering coefficients were measured and used to compute the gap capacitances of the structure.

The gap discontinuities were then used to confirm the theoretical assumed pi-equivalent circuit.

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I. INTRODUCTION

Microwave transmission media are becoming more widely used in current technology. Their applications in radar and missile guidance systems is a principal driving factor behind the attention being devoted to them. Because of their ability to minimize losses, and maintain moderate dispersion characteristics at higher operating frequencies compared to microstrip lines, suspended substrate lines are an important choice for microwave design. Also contributing to their importance is the shielding isolation of the transmission system.

Basic planar microstrip circuitry has been under development for a long period and there is an abundance of literature available on this medium. The shielded suspended-substrate stripline (SSL) is presently in its developmental state and its discontinuity design equations have yet to be verified.

The objective of this thesis is to confirm through measurement the gap and other discontinuities of the SSL structures as applied in microwave filter design. This will be accomplished by designing a test structure which is a prototype of the basic shielded line element used in proposed filter structures. The major limitation in the design is the

availability of adequate milling facilities and laboratory test equipment. This limitation impacts on the possibility of measurements in system-level KA band WR-28 waveguide, so that scaled measurements are made on X-band waveguide models.

Higher frequencies require accurate milling and precision measuring equipment, neither of which is accessible at the location of the present work.

II. SHIELDED SUSPENDED STRIPLINE DESIGN

In order to confirm theoretical values of the SSL gap capacitance discontinues it is necessary to design a structure which allows for the experimental testing of the discontinuities of interest. This chapter describes the analysis process used in designing the device to be tested.

The structure to be tested is composed of a dielectric substrate with a stripline conductor suspended within a shield. Figure 1 is a cross-sectional view of the transmission structure to be tested.

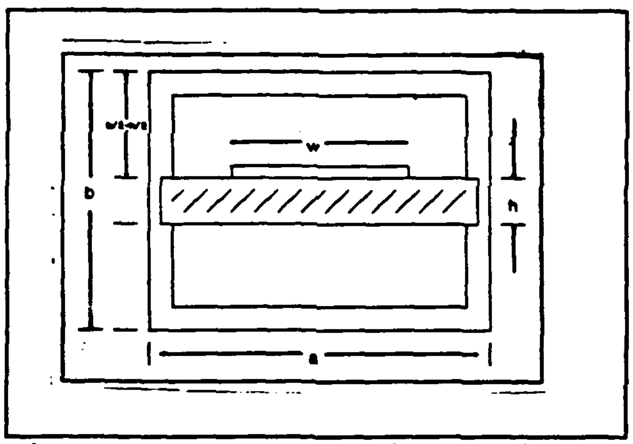


Figure 1. Cross-sectional view of SSL

[Ref. 1] and [Ref. 2] were the available sources of closed-form expressions for the quasi-static transmission parameters of the SSL structure to be tested. The equations governing the design as developed by [Ref. 1] and [Ref. 2] are as given in Appendix A.

Allowing the width of the stripline to vary within an enclosed structure (WR(90) waveguide) on a substrate with ϵ_r = 2.54 (Rexolite) ,Figure 2 shows that the characteristic impedance of the microstrip line decreases as the width of the line is increased.

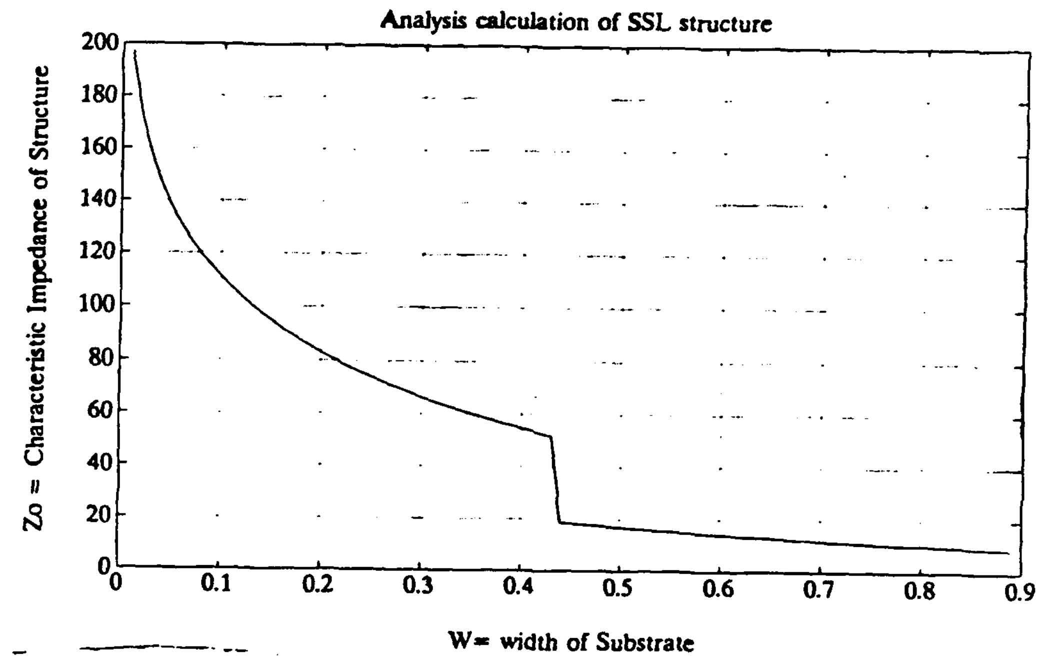


Figure 2. Z_o v. width

Reference 2 shows that the result tends to be within 1% agreement with the least squares curve fitting to data which can be obtained by using Super Compact for the structure of interest. The method incorporated by S-Compact synthesizes a strip width for a given characteristic impedance.

The characteristic impedance is slowly frequency dependent. It is assumed however, that the wave propagation

mode will be quasi-TEM. In order to avoid waveguide mode propagation the functional cutoff frequency of the waveguide must be established.

The functional operating range and waveguide mode cutoff frequency is given by the following equation [Ref. 3]:

$$f_c = \frac{C}{2a}\sqrt{1-\frac{h}{b}\left(\frac{\epsilon_r-1}{\epsilon_r}\right)} \tag{1}$$

where

f_c = cutoff frequency

C = speed of light

[Ref. 3] concludes that from this it can be shown that for relatively low values of substrate permittivity (ϵ_r), the lowest waveguide modes expected will be the LSM_{11} or distorted TE_{01}. This allows the designer of a SSL structure to predict the highest frequency which can be utilized while preventing waveguide mode propagation. This further implies that all useful data must be obtained at frequency below the cutoff-frequency of the structure. The behavior of the structure at frequencies above the cutoff are unpredictable due to unwanted waveguide modes.

To facilitate laboratory measurements and structure construction the test were conducted at frequencies which were easily accessible and optimum for the structure tested.

However, precautions had to be taken to avoid unwanted coupling between components and unwanted resonances. The precautions taken, discussed further in Chapter 3, were particularly important since the waveguide chosen was WR-(90) X band, which is much larger than the K band guides used in previous evaluations. The overall length of the device can not be an integer multiple of any of the stripline wavelengths that will be used to obtain discontinuity measurements. This is necessary to avoid resonance within the shielded structure. The occurrence of resonance is expected to yield inaccurate data.

The design utilized X-band waveguide as the channel to shield the suspended substrate transmission line. As mentioned in the above paragraph the cutoff frequencies of the structure could be calculated. Utilizing equation 1 we find that the cutoff frequency for the chosen X-band waveguide is approximately 5.907 GHz.

A. SUBSTRATE WITH GAP STRIPLINE

The physical layout of the substrate with the stripline gap is shown in Figure 3. The design was based on the expectation that the individual gap was expected to have a series capacitance plus capacitances to ground(shield) due to the fringing fields at the break in the line.

The calculations for the theoretical capacitances were based on work completed by [Ref. 2] and [Ref. 4] .

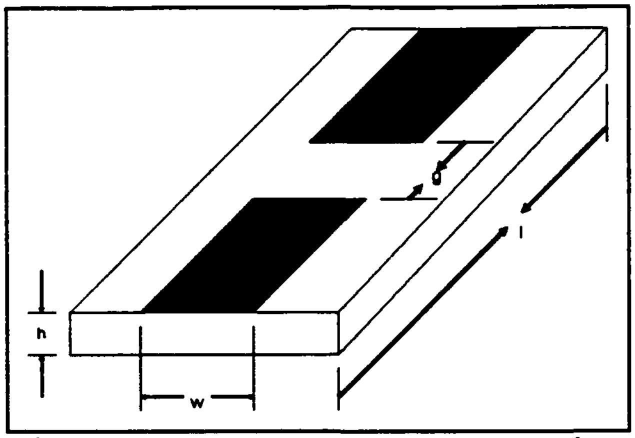


Figure 3. Substrate with stripline conductor

[Ref. 2] used a method which placed a suspended stripline on a substrate in a shielded box with the stripline having a 1/2 gap length at each end an approximate circuit was developed. Figure 4 is a representation of the above mentioned method. This method differs from the quasi-static approach (appendix 1) in determining discontinuities by assuming electric and magnetic walls at the ends of the enclosure and completing two separate calculations to derive the gap capacitance. The first calculation assumes an electric E-field within the shield which has no component perpendicular to the magnetic walls. The second calculation assumes an E-field within the shielded box which has perpendicular components to the end walls. Both calculations then take the assumed fields and express them in the form of finite series summations in which each term is individually a solution to Laplace's equations.

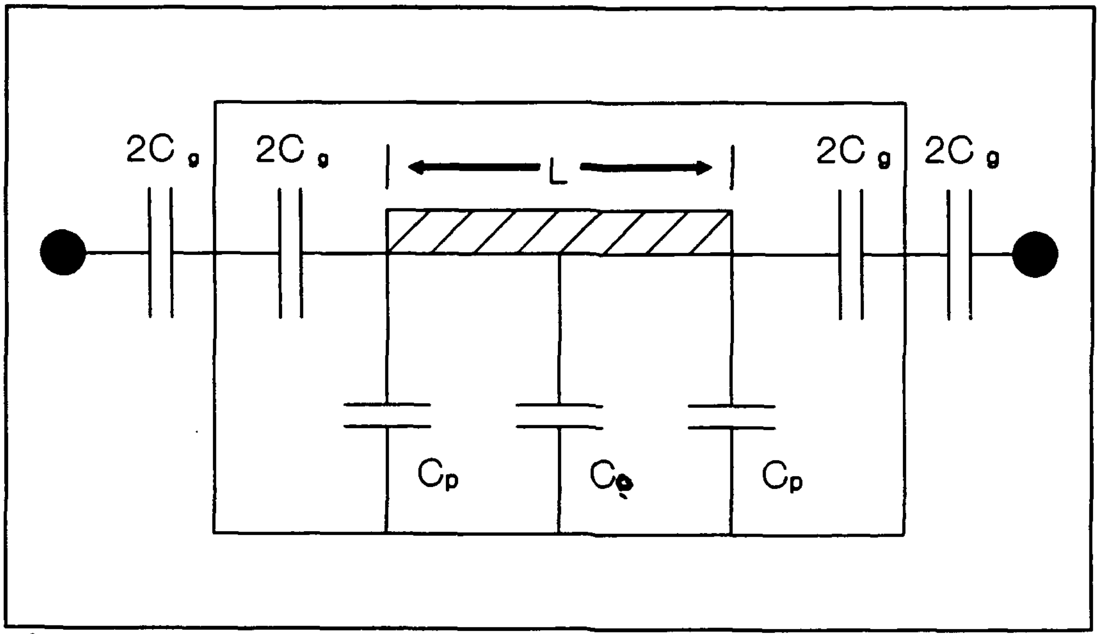


Figure 4. Assumed equivalent circuit[Ref. 2]

where

C_g = the series gap capacitance which represents the electrostatic capacitance between the two open ends of line at the gap. This is represented here by capacitor, $2C_g$ and the image in the end wall of the shield.

C_o = capacitance of the uniform microstrip transmission line with length l.

C_p = parasitic capacitance due to electrostatic field lines extending from open ends to ground.

Once the total capacitance between the line section and the enclosing shield box for the two cases has been computed, the gap capacitance C_g and the parasitic capacitance C_p can be calculated using the following relationship:

$$C_g = \frac{C_E - C_M}{4} \qquad (2)$$

$$C_p = \frac{C_M - C_O}{2} \qquad (3)$$

where

l = length of the strip transmission line, and C_E and C_M are the total capacitances of the strip to ground for the electric and magnetic-wall cases, respectively.

The above method was incorporated in a FORTRAN program which was confirmed by [REF 2.] to compute the gap and parasitic capacitances of a (WR-28) SSL Structure. The program results are depicted in Figure 5. Since the calculations are based on the ratios of a/b and w/a, it can be concluded that the results can be scaled to a separate structure with the same dimensional ratios. Further, it can be concluded that the capacitance of the gaps can be expected to decrease as the size of the gap is increased.

To accurately evaluate the gap capacitance of the structure gap sizes were varied as a function of the width of the waveguide. The measured widths of the stripline range from 1/2 to 1/5 the width of the waveguide and the gap range from 1/5 to 1/2 the width of the stripline. Table 1 outlines the stripline widths and gap sizes tested.

TABLE 1. STRIPLINE DIMENSIONS AND RATIOS

#	WIDTH (in.)	GAP (in.)	w/a	g/w
1	.450	.225	.5	.5
2	.450	.150	.5	.333
3	.450	.1125	.5	.25
4	.300	.150	.333	.5
5	.300	.100	.333	.333
6	.300	.075	.333	.25
7	.225	.1125	.25	.5
8	.225	.075	.25	.333
9	.225	.057	.25	.25

It is expected that the ratio of stripline width to waveguide width and the gap size to waveguide width are the most useful parameters for determining the discontinuities of the transmission structure. Therefore the ratios have been varied for three separate conditions, as summarized in Table 1. This will provide sufficient data to allow for optimum evaluation of the theoretical values.

B. REALIZATION OF SUBSTRATE IN X-BAND WAVEGUIDE

An important consideration in realization of the structure was the effects of the sidewall grooves on the wave propagation within the structure. [Ref. 5]

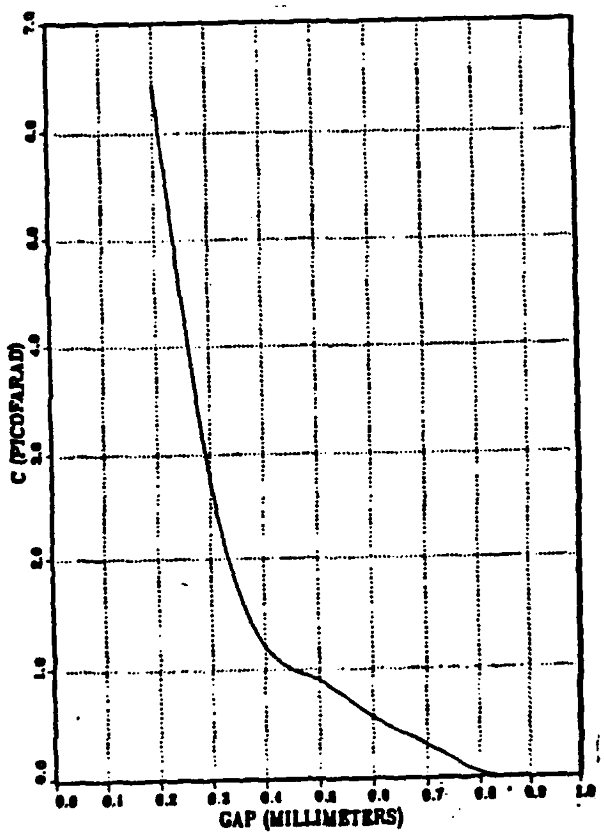


Figure 5. C_g v. size of gap in stripline.

provided the method used on the design structure.

The static capacitance per unit length of a TEM transmission structure can be derived using the expression:

$$W = \frac{Q^2}{2C} \tag{4}$$

where Q is the charge per electrode and C is the capacitance and W the energy required to set up charge Q.

The characteristic impedance and the wavelength reduction are factors of greatest concern. It was shown in [Ref. 5] that sidewall grooves only affected those parameters at relatively deep groove depths. Figure 7 and Figure 8 show the results obtained by [Ref. 5] using Duroid (ϵ_r = 2.22) . Therefore it is assumed that until the grooves approach a depth approximately 1/2 the thickness of the sidewall conductors there is negligible effect on the overall capacitance and wavelength reduction within the structure.

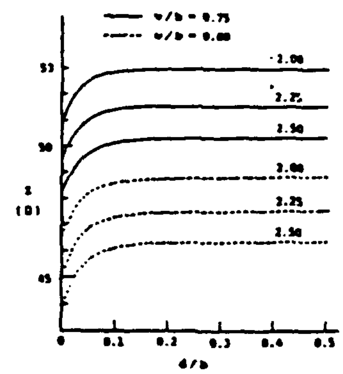


Figure 6. Side-wall groove effects on the characteristic impedance Z_0. a/b=1.0,h1/b=.4,h2/b=.2, h3/b= .4, t=0,ε=2.22

The results were based on ratios of the Shielded SSL structure width to the width of the stripline.

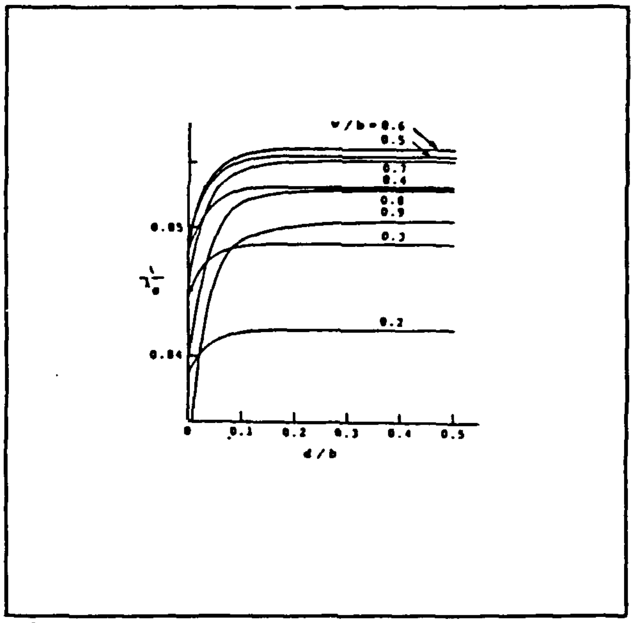


Figure 7. Side-wall groove effects on the wavelength reduction factor λ/λ_0. a/b=1.0, h1/b=0.4, h2/b=0.2, h3/b=0.4, t=0, ϵ=2.22

C. RESULTING SSL STRUCTURE

Figure 9 shows the resulting SSL structure. The housing is a WR-90 X-band waveguide. The suspended substrate is Rexolite (ϵ_r= 2.54) with a copper strip centered on the substrate. The Rexolite was suspended in the waveguide using grooves in the sidewalls shown in Figure 10. The waveguide was cut in the vertical plane and grooved and soft-soldered together again.

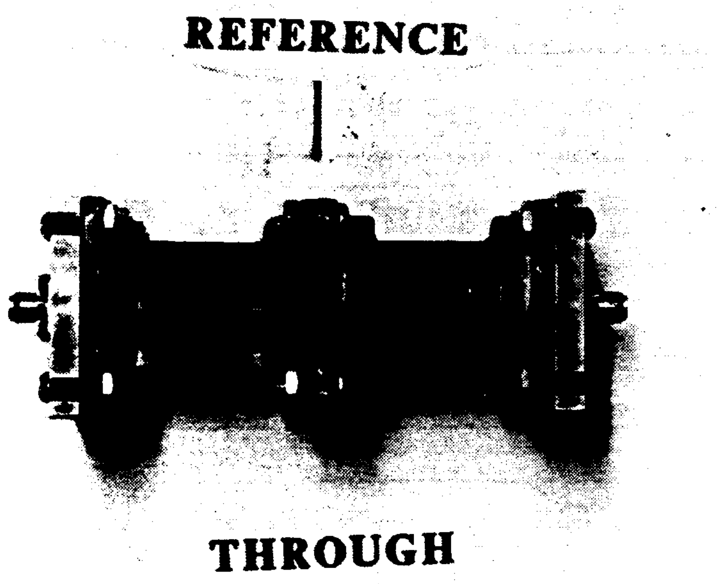


Figure 8. SSL in X-Band (WR-90) Waveguide.

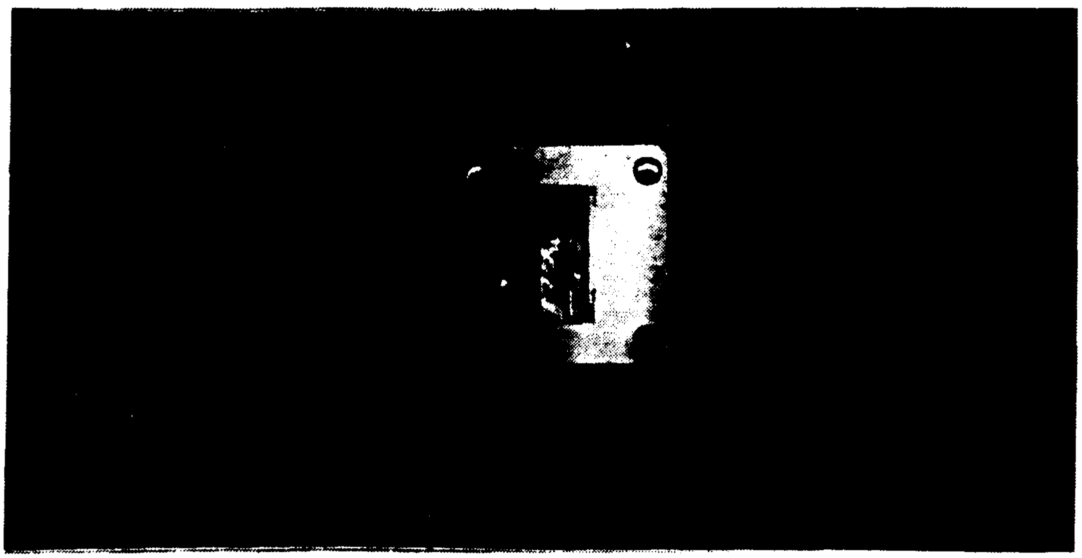


Figure 9. Side- Wall Grooves of SSL Structure.

III. DISCONTINUITY-NETWORK CHARACTERIZATION

A common description or representation of a given two port microwave device is the matrix representation. Two examples are the scattering and transmission matrices which characterize device discontinuities:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} * \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} * \begin{bmatrix} a_2 \\ b_2 \end{bmatrix} \tag{6}$$

where a_i and b_i are the ingoing and outgoing phasor wave amplitudes at the i^{th} port, respectively. The R-matrix is given in terms of the S-matrix by:

$$[R] = \frac{1}{S_{21}} \begin{bmatrix} -d_s & S_{11} \\ -S_{22} & 1 \end{bmatrix} \tag{7}$$

where

$$d_s = S_{11}S_{22} - S_{12}S_{21} \tag{8}$$

The R-matrix sometimes referred to as the "transmission-matrix" has properties similar to the ABCD matrix, in that a cascade connection of two-ports has an R-matrix of the product of the individual matrices of the cascaded elements, in the order of their connection.

The matrix representation becomes particularly useful when characterizing microwave structures and devices. Characterization of microwave structures is accomplished by use of the scattering matrix. A more detailed discussion of the scattering matrix and its relative merits in microwave structure characterization can be found in [Ref. 6].

A. DETERMINING THE SCATTERING COEFFICIENTS

The scattering parameters or S-parameters as previously discussed are defined in terms of forward and reverse traveling waves at the ports of a device. The S-parameters can be measured using a Microwave Network Analyzer.

The analyzer chosen to accomplish the required measurements was the HP 8410-Series Network Analyzer System. Figure 10 is a diagram of the system.

HP-8410A Network Analyzer System and the 11863E Accuracy Enhancement Pac is a program executable on the HP 9845T desktop computer which is written to drive the 8410A Network Analyzer. The program provides two calibration error models for measuring multiport devices in the 2-18 GHz frequency range and also computes group delays from the phase data.

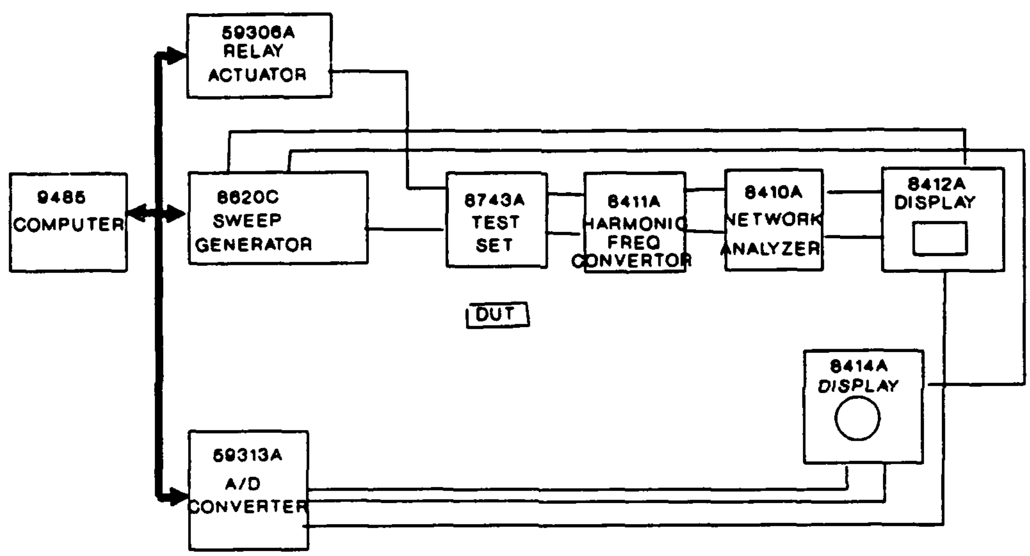


Figure 10. HP-8410a Network Analyzer System

Error correction is achieved by the eight term error model or the twelve term error model.

The Eight Term Error model provides directivity, source match, and frequency response vector error correction for reflection measurements and frequency-response-only vector error correction for transmission measurements. The eight term error model is generally used on single port devices, however when fast normalized magnitude and phase frequency response is adequate this model may be used on multi-port devices.

The twelve term model provides full directivity, isolation, source match, load match, and frequency response vector error correction for transmission and reflection measurements. This model is utilized when maximum accuracy of reflection and transmission characteristics of multi-port devices is essential.

B. TESTING THE SSL STRUCTURE

To measure the S-parameters of device under test it is necessary to make a transition from the stripline to the coaxial cable used by the HP Network Analyzer. [Ref. 7] discusses several microwave transition designs and discusses some of the questions associated with a transition of one microwave subsystem to another.

1. The Transition

A microwave transition is the mechanism which allows electromagnetic waves on one type of transmission line to be coupled into another type, such as the suspended stripline to coaxial transition required in this case. Several considerations are important in transitions, of which are the maximization of coupling and minimization of reflections (matching impedance), efficient wave transition from one medium to another and a gradual field match. A gradual field match is achieved by smoothly transitioning from one mode of propagation in a medium to another mode of propagation an the other medium.

Coaxial cable under normal operating conditions, is expected to support only TEM wave propagation. Since the frequency range chosen for the test is 2.0 - 4.0 GHz, below the cut-off frequency of the X-band wave guide, this becomes a useful characteristic.

Connecting the coaxial cable to the measuring assembly requires the use of a transition. A broad range of transition connectors are available to the engineer. However each has characteristics which are more suitable for a given frequency range. Table 2 lists some of the more common connectors and their operating frequency ranges.

The connector type chosen for the transition was the SMA. The connector meets the specifications of the design

and transitions are available to the APC-7 connector used by the HP Network Analyzer.

The SMA connector was mounted to a faceplate and soldered to the stripline. Figure 12 shows the configuration. The objective is to achieve an impedance match and minimize the possibility of fringing fields. However, the transition was still not perfectly matched because of the disparity of the dimensions of the connector center lead and the stripline.

TABLE 2. AVAILABLE MICROWAVE TRANSITIONS

CONNECTOR TYPE	MIL-SPEC	FREQUENCY RANGE	BAND DESIGNATION
N	MIL-C-39012/1/5	0-12 GHz	VHF,UHF,L,S, C,X
C	MIL-C-39012/6-15	0-12 GHz	VHF,UHF,L,S, C,X
BNC	MIL-C-39012/16/24-1	0-4.0 GHz	VHF,UHF,L,S
TNC	MIL-C-39012/26/34	0-12 GHz	VHF,UHF,L,S, C,X
SC	MIL-C-39012/35/43	0-12 GHz	VHF,UHF,L,S, C,X
SMA	MIL-C-39012/55/62	0-12.4 GHz	VHF,UHF,L,S, C,X

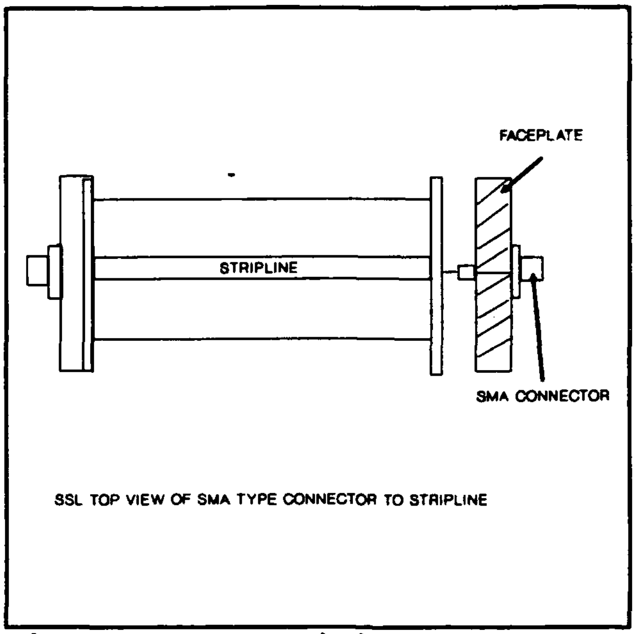


Figure 11. Transition Connectors

C. RESULTS

Appendix B lists the measured S-parameters of gap discontinuities in the SSL structure tested. In cases where gap sizes were to small to be accurately etched using the available facilities the data was not recorded.

IV. DE-EMBEDDING DATA WITH TRL

The HP Network Analyzer provided two-port S-parameters which included the effects of line and transition reflections and losses. As in most discontinuity examples of interest, the device(the gap) is embedded within the transmission medium. Measurements obtain by the HP Network Analyzer include the effects of the embedding transmission media. Since the transitions are not ideal and the parameters are not well known, it becomes impossible to de-embed using elementary methods. At mm-wavelengths, a de-embedding procedure called the through-reflect-load (TRL) allows the use of non-ideal elements in the procedure [Ref. 8]. The non-ideal elements are, T, the through line that connects the transitions on the two sides of the device under test; R, the reflecting terminations that can be anything as long as identical ones are used to terminate both the input and output transitions; and L, a length of transmission line connecting the two transitions.

A. METHOD EMPLOYED IN TRL

[Ref. 8] outlines a method of de-embedding mm-wave MICs with TRL which is very useful in this case. Figure 16 shows the four measurements required for TRL de-embedding.

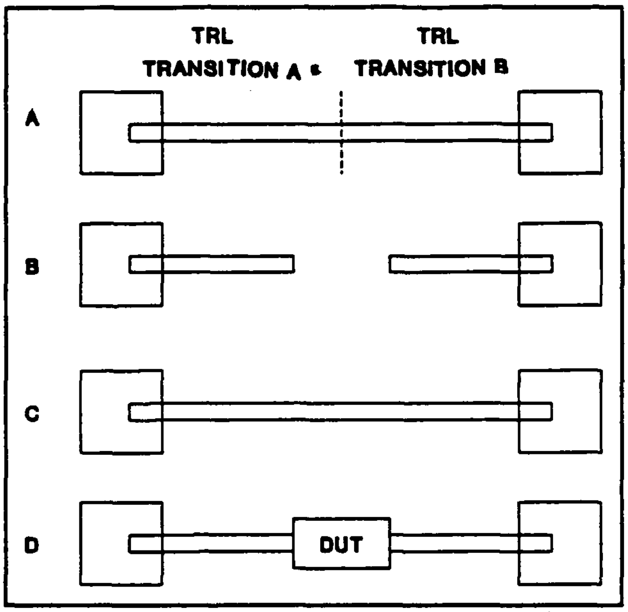


Figure 12. Four required measurements of TRL de-embedding

The coupling transitions A and B are not required to be of equal length , however must meet at the reference position. Further, there is not a requirement for the transitions have the same connection to the analyzer ports. The reflect measurements used may be any two identical reflections, ideally they should utilize equal sections from each side of the reference position (see Figure 12B). The line or length portion of the measurement is obtained by the addition of a length of line at the reference position of the A and B transitions. Figure 13 is a block diagram of the TRL procedure and the assumed S-parameters values for each step provided by [Ref. 9].

Appendix A is an excerpt from [Ref. 7] which describes the mathematics behind the TRL procedure. The author,

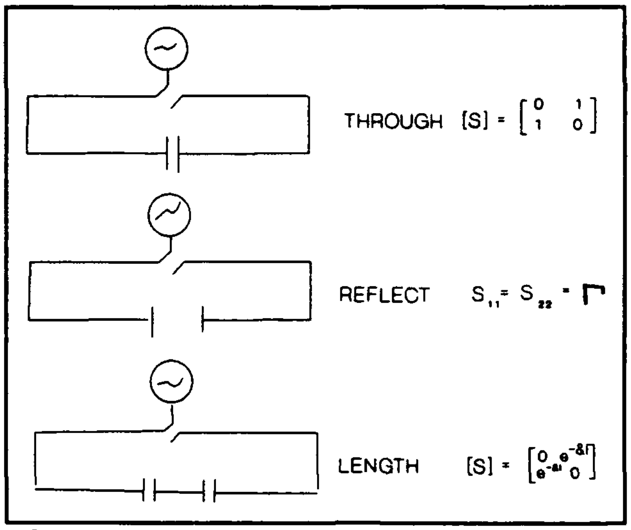


Figure 13. TRL Procedure and Assumed S-parameters

[Ref.7], also provided a program written in True Basic which incorporates the mathematical procedure outlined in Appendix B which was essential in de-embedding the DUT.

Figures 14 through 17 show the different parts of the device used to obtain the four required measurements for the de-embedding process. Each of the four required measurements were conducted for each width of stripline used for the overall analysis of the microwave subsystem.

The resulting data obtained from each of the required measurements shows that for the various widths of stripline used on the substrate the S-parameters are approximately consistent as a function of frequency. It also shows that the "Reflect" loss increases as the wave guide mode is approached.

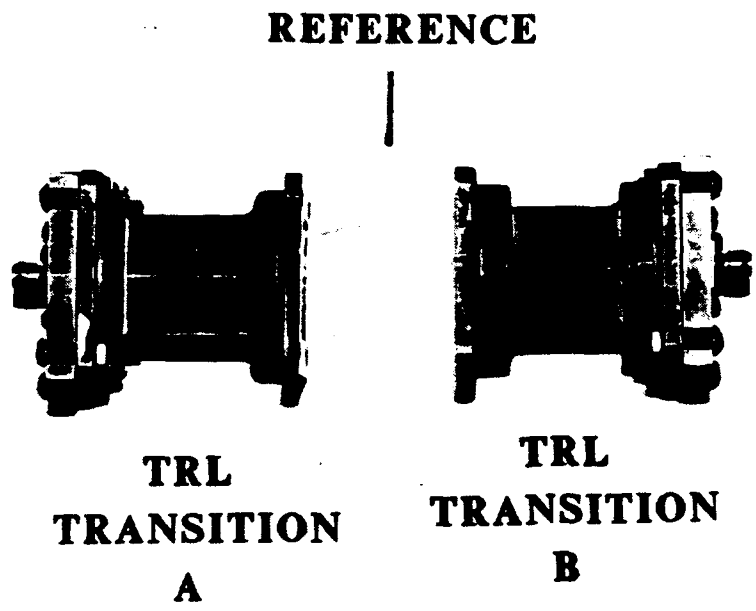


Figure 14. TRL Transitions A and B.

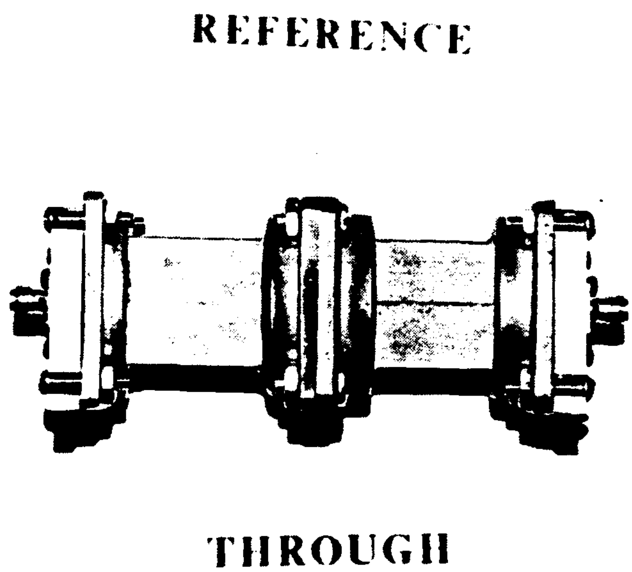


Figure 15. Through measurement

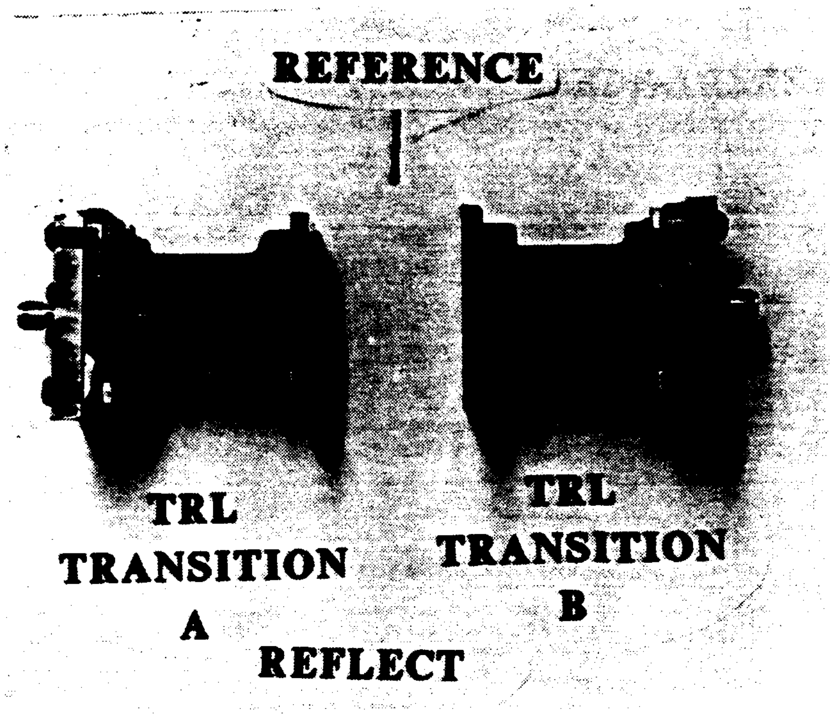


Figure 16. Reflect Measurements

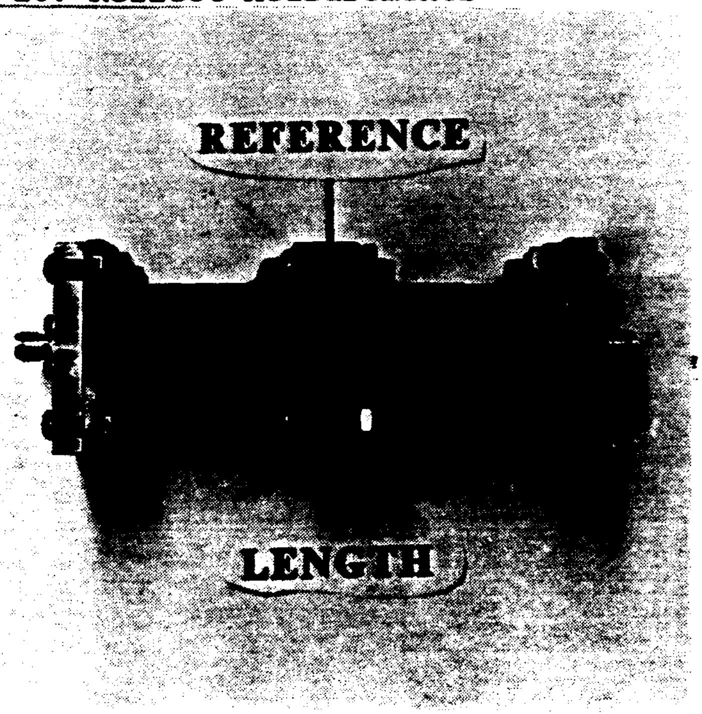


Figure 17. Length Measurement

V. DISCONTINUITY EVALUATION

A. S-parameters to Admittance matrix

In order to relate the measured scattering parameters of the SSL device to an equivalent circuit, the first step is to relate the S-parameters to the admittance parameters of an assumed equivalent circuit. The generalized assumed equivalent pi-circuit of gap discontinuities are pictured in Figure 18.

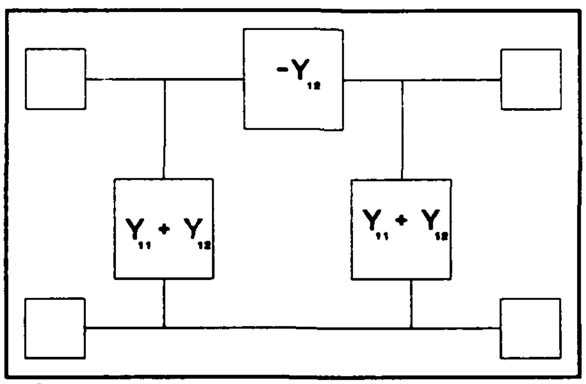


Figure 18. Generalized admittance pi-circuit [Ref. 4]

The admittance matrix of the circuit is:

$$[Y] = Y_o \begin{vmatrix} Y_{11} & Y_{21} \\ Y_{21} & Y_{22} \end{vmatrix} \tag{9}$$

where $Y_{i,j}$ are the normalized admittances and $Y_o = 1/Z_o$ is the characteristic admittance of the SSL transmission line.

Calculations of Z_0 are depicted in Appendix A for the SSL structure.

For any lossless, reciprocal, symmetric 2-port network, the normalized admittances can be related to the S-parameters using the following relationship:

$$y_{11}=y_{22}=-j\left[\frac{\sin\theta_{11}}{(\cos\theta_{11}+|S_{11}|)}\right] \tag{10}$$

$$y_{21}=y_{12}=\frac{j[(1-|S_{11}|^2)^{\frac{1}{2}}]}{[\cos\theta_{11}+|S_{11}|]} \tag{11}$$

The scattering parameters measured from the device can be related to the admittance matrix of the equivalent pi circuit . The assumed pi-circuit is depicted in Figure 19. The elements of the admittance matrix given in equation 9 in terms of the two-port discontinuity is:

$$Y_{11}=-jY_o\left[\frac{(\sin\theta_{11}-|S_{21}|)}{(\cos\theta_{11}+|S_{11}|)}\right] \tag{12}$$

$$Y_{21}=-jY_o\left[\frac{|S_{11}|}{(\cos\theta_{11}+|S_{11}|)}\right] \tag{13}$$

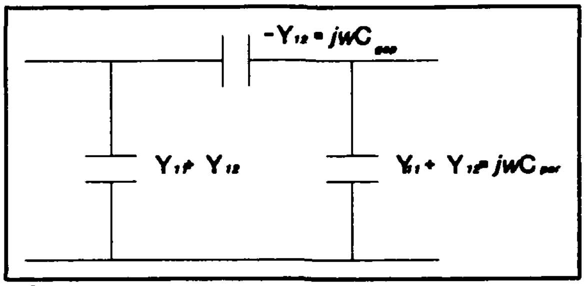


Figure 19. Network Parameters

B. Synthesis of equivalent circuit

As shown in the previous discussion the measured data can be related to the admittance parameters of the assumed equivalent circuit using equations 12 and 13. Once the admittance parameters have been concluded the equivalent circuit is then derived using the methodology established in [Ref. 4]. The admittance parameters derived from the measured data provided the necessary data for calculation of the discontinuity capacitances, C_{gap} and C_{par} using the following relationships:

$$-Y_{12}=j\omega C_{gap} \tag{14}$$

and

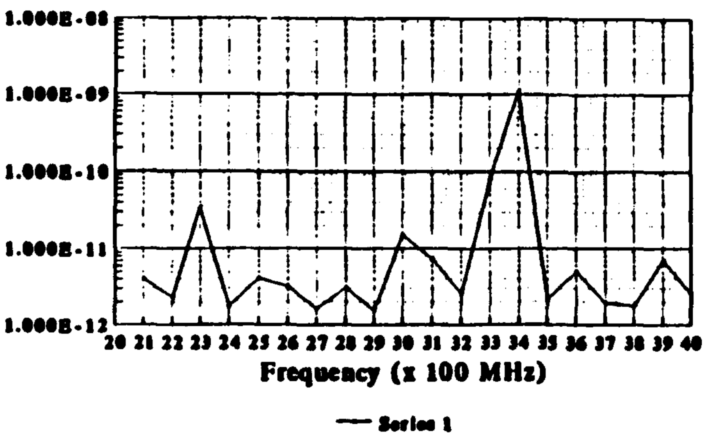
$$Y_{11}+Y_{12}=j\omega C_{par} \tag{15}$$

The following capacitances were calculated from the measured data using the methodology previously discussed:

Table 3. CALCULATED GAP AND FRINGING CAPACITANCE W= .450" AND G= .225". . . . .

Frequency (GHz)	Cgap pfarads	Cpar pfarads
2.1	6.024	-6.028
2.2	2.202	1.718
2.3	34.87	15.36
2.4	1.742	.2329
2.5	6.137	-6.375
2.6	3.179	.6182
2.7	1.61	.0055
2.8	3.086	1.455
2.9	1.554	.0594
3.0	.1508	-1304.0
3.1	7.435	-5.727
3.2	2.595	1.063
3.3	81	18.37
3.4	1123	-56.58
3.5	2.18	2.164
3.6	5.025	6.221
3.7	1.958	-1.912
3.8	1.778	-1.726
3.9	7.119	-4.946
4.0	2.515	2.439

Calculated Gap Capacitance
w=.450" g=.225"



Calculated Fringing Capacitance
w=.450" g=.225"

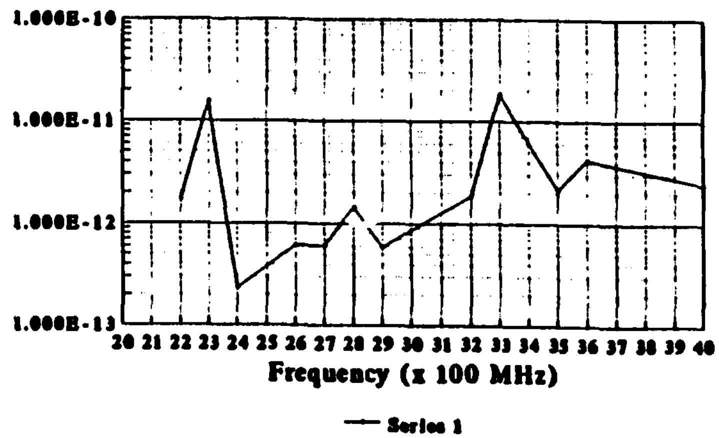


Figure 20. Calculated Gap and Fringing Capacitances

w = .450" g= .225"

Table 4. CALCULATED GAP AND FRINGING CAPACITANCE W= .450" AND G=.150". . . . .

Frequency (GHz)	Cgap pfarads	Cpar pfarads
2.1	2.306	-1.792
2.2	2.56	2.249
2.3	2.508	-2.371
2.4	1.737	.006905
2.5	4.167	-8.65
2.6	3.199	-2.677
2.7	1.645	.7582
2.8	2.995	1.221
2.9	1.554	.6258
3.0	2.773	2.773
3.1	9.736	-6.757
3.2	2.611	1.744
3.3	2.178	2.137
3.4	1.357	.3849
3.5	1.413	1.019
3.6	2.006	2.828
3.7	7.706	-5.444
3.8	1.41	-1.175
3.9	107.5	13.44
4.0	121.4	11.12

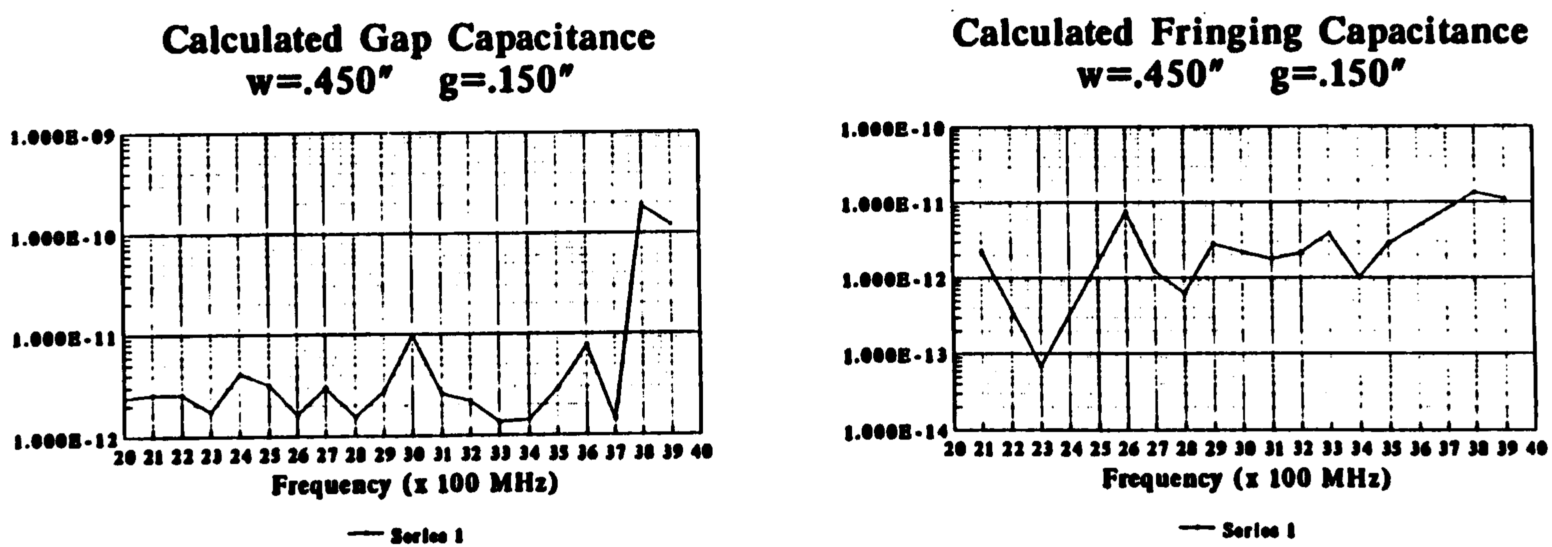


Figure 21. Calculated Gap and Fringing Capacitances

w = .450" g= .150" . . . .

Table 5. CALCULATED GAP AND FRINGING CAPACITANCE W= .300" AND G=.150" . . . .

Frequency (GHz)	Cgap pFarads	Cpar pFarads
2.1	3.172	2.668
2.2	2.517	.204
2.3	1.975	-.1602
2.4	2.577	2.237
2.5	8.706	3.3
2.6	1.629	1.050
2.7	1.405	-.5805
2.8	3.030	.7947
2.9	5.714	.7499
3.0	6.030	2.103
3.1	1.651	.9611
3.2	205.5	-25.05
3.3	.9062	-.2174
3.4	1.82	1.495
3.5	1.28	.3709
3.6	5.707	-3.336
3.7	40.18	-18.07
3.8	67.92	-61.03
3.9	2.66	.9208
4.0	1.743	1.489

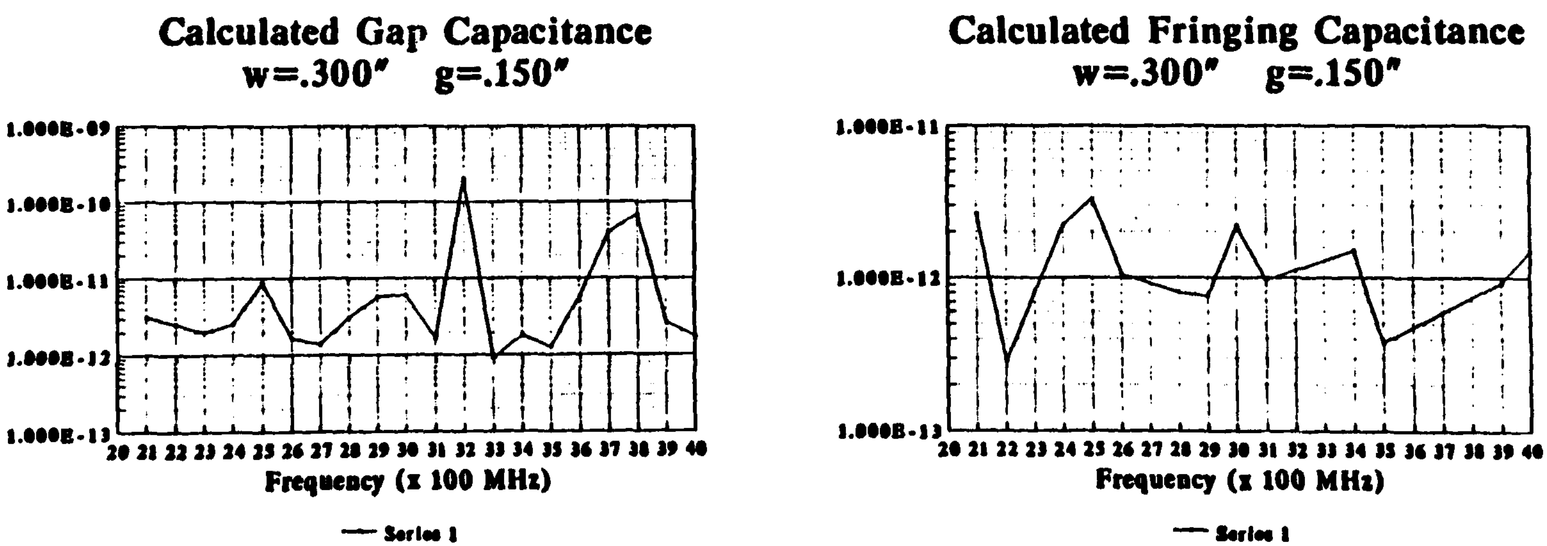


Figure 22. Calculated Gap and Fringing Capacitances w = .300" g= .150" . . . .

Table 6. CALCULATED GAP AND FRINGING CAPACITANCE
W= .300" AND G=.075"

Frequency (GHz)	Cgap pFarads	Cfr pFarads
2.1	3.239	2.501
2.2	2.612	-.9486
2.3	2.816	-.343
2.4	2.481	2.447
2.5	2.229	1.979
2.6	1.335	.6355
2.7	1.233	.075
2.8	1.598	-.5067
2.9	1.363	.09
3.0	1.417	-.7981
3.1	1.047	.471
3.2	2.727	-2.528
3.3	.9825	.3657
3.4	5.281	3.656
3.5	.9877	-0.009
3.6	.947	.2916
3.7	.0531	.1569
3.8	1.19	1.086
3.9	1.326	1.173
4.0	.9805	.6926

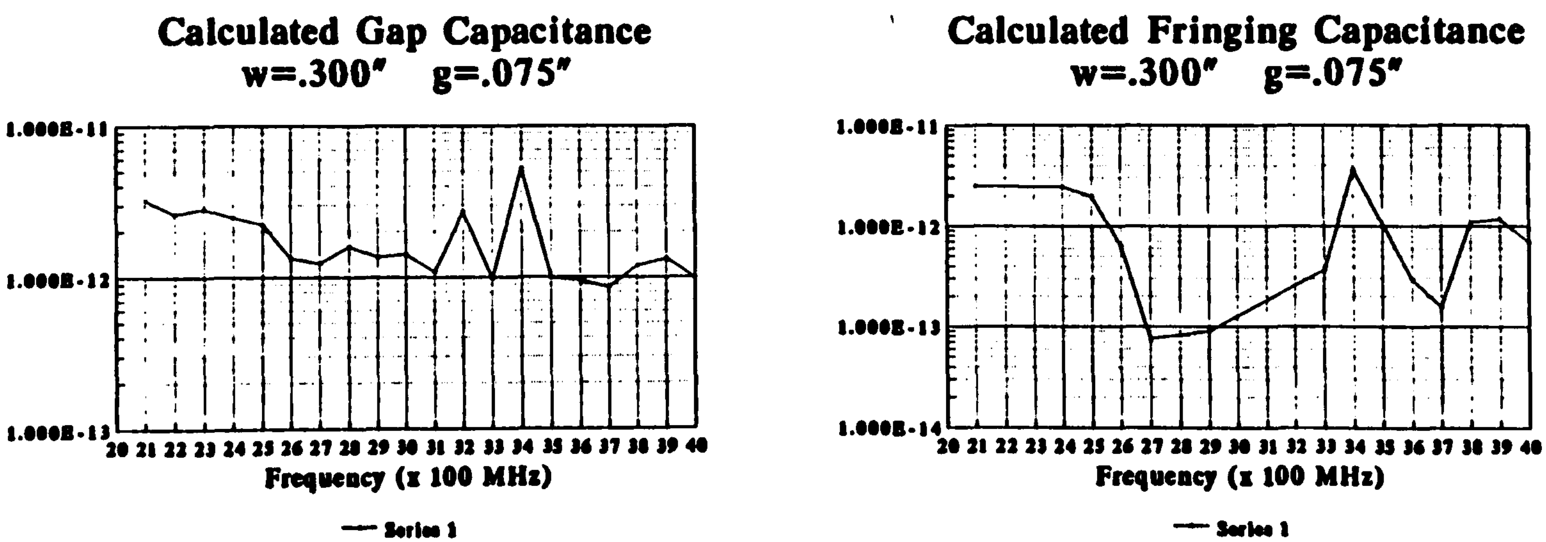
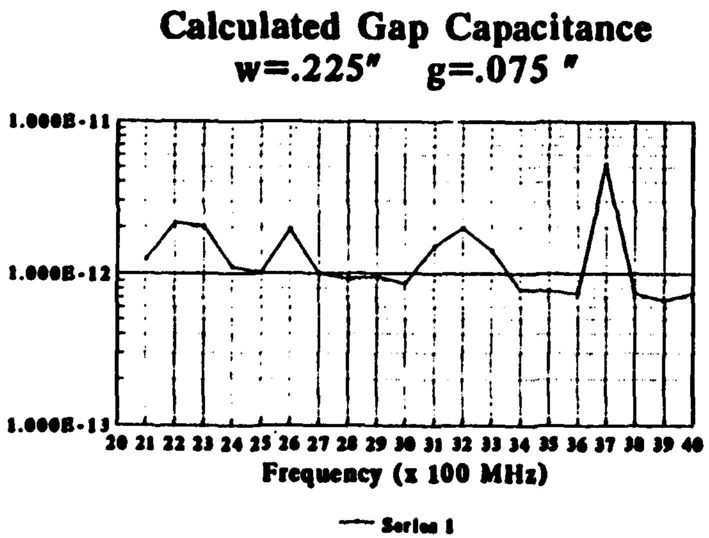


Figure 23. Calculated Gap and Fringing Capacitances

W = .300" g= .075"

Table 7. CALCULATED GAP AND FRINGING CAPACITANCE
W= .225" AND G=.075".

Frequency (GHz)	Cgap pfarads	Cpar pfarads
2.1	1.239	.5983
2.2	2.157	1.590
2.3	2.04	
2.4	1.101	-.007
2.5	1.017	-.2673
2.6	1.952	
2.7	1.00	0.53
2.8	.9267	.1196
2.9	.949	.5592
3.0	.8529	.3546
3.1	1.514	-1.56
3.2	1.907	0.01916
3.3	1.41	-0.9772
3.4	.7832	-0.1648
3.5	.77	-0.2145
3.6	.7394	-0.07479
3.7	5.294	2.446
3.8	.7461	-0.02932
3.9	.6637	.03161
4.0	.7453	-0.3576



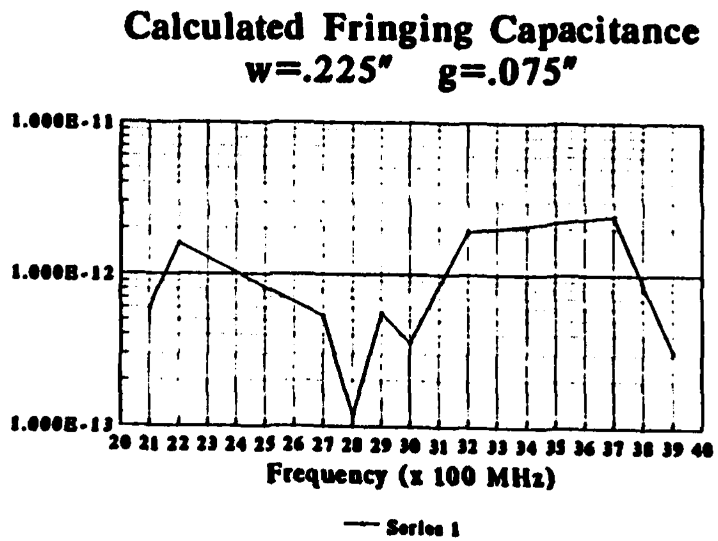
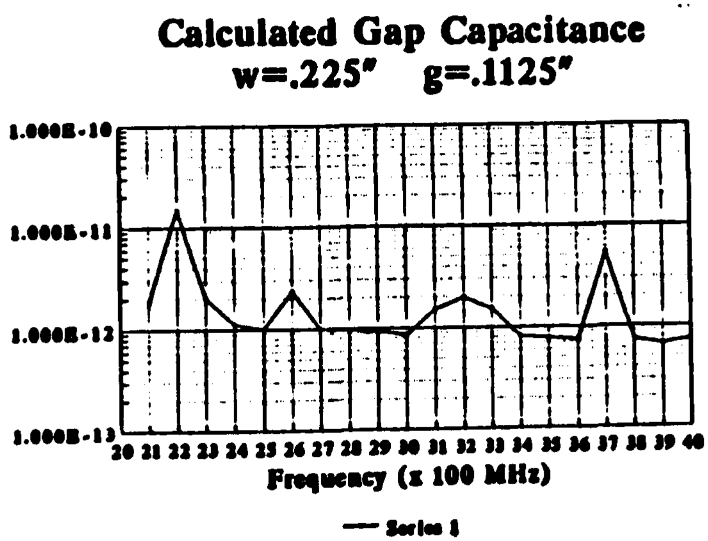


Figure 24. Calculated Gap and Fringing Capacitances

W = .225" g= .075"

Table 8. CALCULATED GAP AND FRINGING CAPACITANCE
W= .225" AND G=.1125"

Frequency (GHz)	Cgap pFarads	Cpar pFarads
2.1	1.041	.1205
2.2	15.11	-3.853
2.3	2.025	1.956
2.4	1.12	-0.1267
2.5	1.017	-0.2705
2.6	2.344	-87.37
2.7	1.001	0.5337
2.8	.072	-0.1322
2.9	.048	0.5572
3.0	.0538	0.3507
3.1	1.53	1.019
3.2	1.969	1.004
3.3	1.521	.2912
3.4	.0118	-0.1134
3.5	.7839	-0.2470
3.6	.7415	-0.062
3.7	5.321	2.503
3.8	.7447	-0.2753
3.9	.6635	0.314
4.0	.7465	-0.375



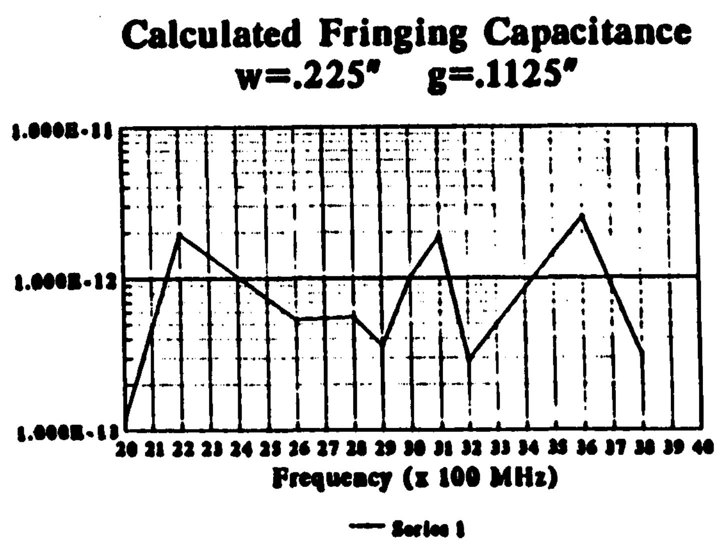


Figure 25. Calculated Gap and Fringing Capacitances

w = .225" g= .1125"

VI. CONCLUSIONS

The objective of this thesis was to evaluate the gap discontinuities of the Shielded Suspended Stripline transmission medium. The methodology followed closely to that developed by Choi [Ref. 4] in his analysis. There were two significant differences between the methods employed in [Ref. 4] and in this thesis to evaluate the gap discontinuities. The most significant difference was the technique employed in measurement. However, the results obtained by both techniques yielded capacitances which proved to be strongly frequency dependent. The magnitudes of the gap capacitances obtained in this thesis are approximately equal to the magnitudes obtained in [Ref. 4].

At some frequencies between 2.0 GHz and 4.0 GHz erratic capacitances are noted, this can possibly be due to resonance of the waves within the shield.

The second significant difference was the frequency at which the test were conducted. The lower frequencies utilized by this thesis appear to substantiate the hypothesis that the SSL structure yields lower losses at higher frequencies. Thus it is believed that the data obtained should be further verified at higher bands using the techniques employed in this thesis.

The fringing or parallel capacitances as expected acted inversely to the gap dimensions.

Recommendation: The results obtained in this thesis need to be further confirmed at higher frequencies using similar techniques. The erratic data obtained at certain frequencies should be further investigated to determine the cause.

APPENDIX A. Quasi-Static Analysis of SSL

The characteristic impedance of the structure can be expressed as

$$Z_0 = \frac{Z_0}{\sqrt{\epsilon_e}} \tag{16}$$

where:

- ϵ_e is the effective dielectric constant of the SSL.

The quasi-static value of the effective dielectric constant is given

$$\sqrt{\epsilon_e} = [1+(E-F\ln\frac{w}{b})\ln\frac{1}{\sqrt{\epsilon_r}}]^{-1} \tag{17}$$

where:

- ϵ_r is the dielectric constant of the substrate.
- for $0 < w < a/2$,

$$E = 0.2077+1.2177(\frac{h}{b})-0.08364(\frac{a}{b}) \tag{18}$$

$$F = 0.03451-0.1031(\frac{h}{b})+0.01742(\frac{a}{b}) \tag{19}$$

- for $a/2 < w < a$ then,

$$E=0.4640+0.9647\left(\frac{h}{b}\right)-0.2063\left(\frac{a}{b}\right) \tag{20}$$

$$F=-0.1424+0.3017\left(\frac{h}{b}\right)-0.02411\left(\frac{a}{b}\right) \tag{21}$$

The characteristic impedance Z_o is given as:

- for a < w < a/2

$$\sqrt{\epsilon_e}Z_o=\frac{\eta_o}{2\pi}\left[V+R\ln\left(\frac{6b}{w}+\sqrt{1+\frac{4}{\left(\frac{w}{b}\right)^2}}\right)\right] \tag{22}$$

where

$$\eta_o=120\pi \tag{23}$$

$$V=-1.7866-0.2035\left(\frac{h}{b}\right)+0.4750\left(\frac{a}{b}\right) \tag{24}$$

$$R=1.0835+0.1007\left(\frac{h}{b}\right)-0.09457\left(\frac{a}{b}\right) \tag{25}$$

- for a/2 < w < a

$$\sqrt{\epsilon_e}Z_o=\eta_o\left[V+R\left[\frac{w}{b}+1.3930+0.6670\ln\left(\frac{w}{b}+1.444\right)\right]^{-1}\right] \tag{26}$$

where

$$V=-0.6301-0.07082\left(\frac{h}{b}\right)+0.2470\left(\frac{a}{b}\right) \tag{27}$$

$$R=1.9492+0.1553\left(\frac{h}{b}\right)-0.5123\left(\frac{a}{b}\right) \tag{28}$$

The design equations are valid for:

$1 < a/b < 2.5$

$1 < \epsilon_r <$ [illegible]

$0.1 < h/b < 0.5$

APPENDIX B. Measured S-Parameters

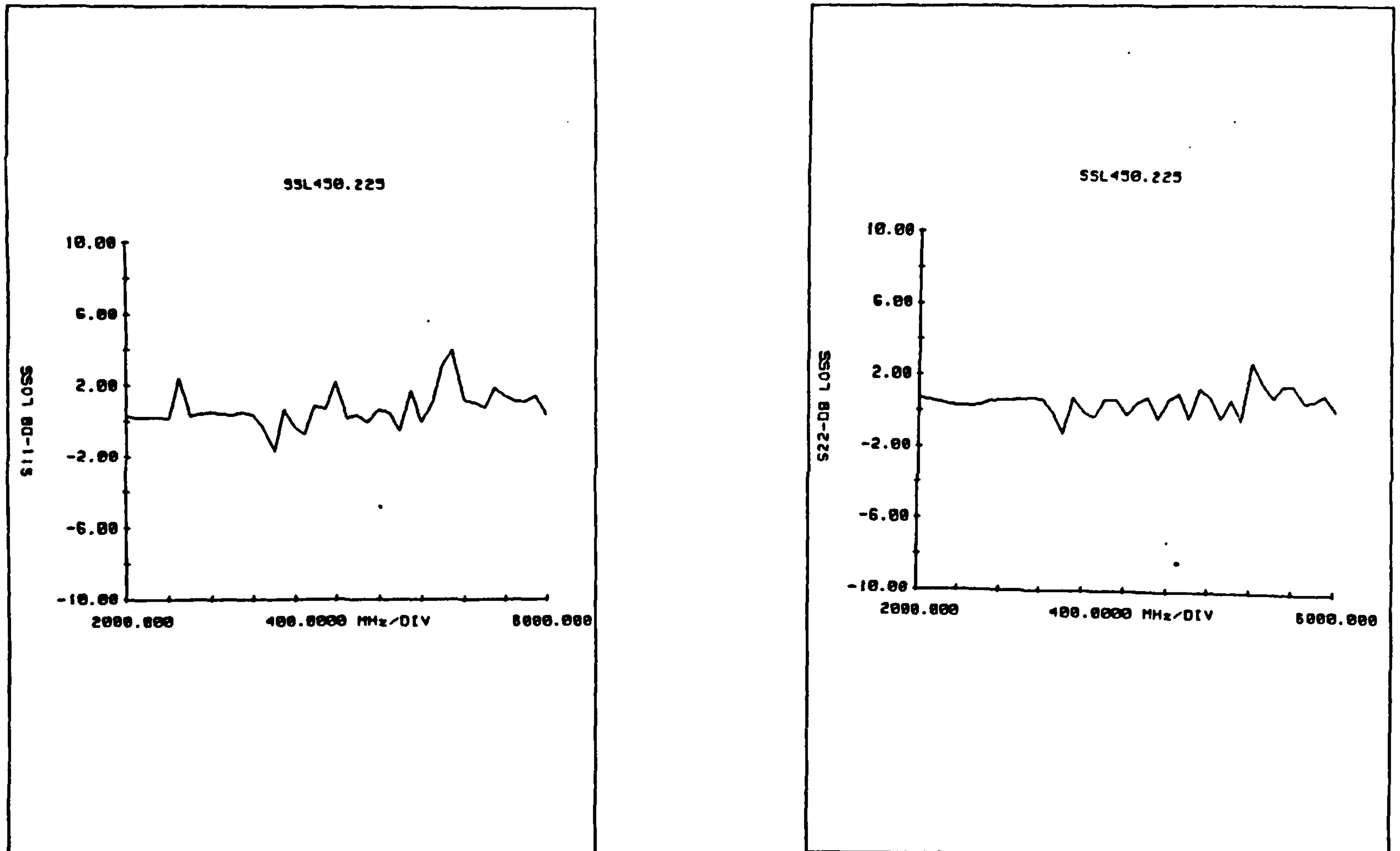
The following is the data collected of the SSL structure using the HP Network Analyzer. The data is assumed accurate since the twelve term error model discussed previously was used.

Table 9. MEASURED S-PARAMETERS OF SHIELDED SSL
W= .450" AND G= .225"

SSL450.225

FREQUENCY MHz	RETURN LOSS-IN S11 DB	RETURN LOSS-IN S11 ANG	LOSS-FORWARD S21 DB	LOSS-FORWARD S21 ANG	DELAY u-SEC	LOSS-REVERSE S12 DB	LOSS-REVERSE S12 ANG	RETURN LOSS-OUT S22 DB	RETURN LOSS-OUT S22 ANG
2000.0000	.30	-156.9	27.38	-74.8	.0010	29.14	-74.1	.71	175.4
2100.0000	.21	168.4	27.01	-111.6	.0010	28.98	-110.8	.62	140.4
2200.0000	.18	134.4	26.10	-146.8	.0019	28.05	-147.1	.45	107.6
2300.0000	.17	97.1	24.64	-146.0	.0005	24.04	137.1	.31	70.6
2400.0000	.14	65.0	22.33	126.7	.0099	20.45	123.7	.25	39.5
2500.0000	2.32	44.8	21.77	130.5	.0011	26.03	146.7	.29	5.5
2600.0000	.24	-1.2	23.31	91.6	.0030	26.64	86.0	.34	-20.7
2700.0000	.38	-29.7	26.09	-16.5	.0003	28.45	-6.4	.51	-47.9
2800.0000	.44	-60.3	21.85	-26.3	.0070	22.96	-20.5	.62	-78.0
2900.0000	.42	-84.3	24.04	81.8	.0018	25.66	93.8	.64	-101.7
3000.0000	.35	-111.6	31.00	17.6	.0015	33.36	27.6	.65	-128.1
3100.0000	.45	-135.8	18.11	-37.8	.0039	18.67	-30.2	.73	-153.5
3200.0000	.35	-155.9	36.06	-178.5	.0094	-11.84	-45.0	.70	-173.3
3300.0000	-.40	-179.4	27.69	-158.6	.0074	-11.37	-176.9	-.05	161.9
3400.0000	-1.75	164.4	17.79	-65.1	.0034	-11.98	54.6	-1.28	145.3
3500.0000	.61	137.1	29.92	171.3	.0029	-10.27	-79.9	.76	113.0
3600.0000	-.34	112.9	26.77	65.3	.0057	-9.17	150.8	-.09	88.3
3700.0000	-.82	100.2	25.02	-138.5	.0030	-8.27	28.3	-.28	74.1
3800.0000	.84	78.9	35.76	112.4	.0091	-4.93	-90.8	.67	48.3
3900.0000	.66	71.2	28.30	145.9	.0005	-4.04	154.4	.67	32.4
4000.0000	2.12	36.4	28.13	129.6	.0008	3.52	46.5	-.19	7.2
4100.0000	.15	25.7	26.14	101.2	.0003	11.00	-102.4	.53	-19.8
4200.0000	.36	2.9	29.72	89.1	.0011	9.32	-73.7	.79	-31.8
4300.0000	-.07	-17.9	23.29	50.2	.0006	.97	173.1	-.34	-56.8
4400.0000	.63	-43.0	26.32	29.6	.0016	-3.13	39.1	.72	-85.8
4500.0000	.47	-62.2	22.96	-27.8	.0095	-4.63	-89.3	1.04	-103.8
4600.0000	-.55	-92.2	18.05	-9.1	.0013	-6.77	136.7	-.36	-132.9
4700.0000	1.67	-134.4	21.48	-55.5	.0015	-6.76	-24.2	1.38	177.0
4800.0000	-.10	-154.2	12.74	-108.8	.0015	-7.90	-178.5	.09	153.8
4900.0000	1.03	114.3	15.57	-163.5	.0086	-5.30	-7.4	*.31	71.5
5000.0000	3.07	-53.1	14.44	-111.8	.0037	-2.17	-85.8	.77	2.2
5100.0000	3.93	66.8	13.84	115.1	.0019	1.22	45.7	-.46	-33.4
5200.0000	1.20	6.2	18.27	46.1	.0092	12.41	39.2	2.84	-44.7
5300.0000	1.05	-32.7	20.66	74.2	.0062	.46	-109.5	1.73	-89.8
5400.0000	.72	-65.3	34.86	-148.5	.0066	-3.09	117.8	.05	-119.4
5500.0000	1.87	-100.6	15.90	-26.2	.0090	-5.28	-19.7	1.55	-154.2
5600.0000	1.38	-115.6	20.82	11.1	.0051	-6.35	-136.8	1.61	-166.5
5700.0000	1.07	-147.7	19.21	-171.6	.0079	-6.57	91.8	.67	168.1
5800.0000	1.09	-166.6	21.68	-94.4	.0080	-5.68	-24.4	.77	150.1
5900.0000	1.38	178.2	21.50	-21.6	.0045	-5.01	-145.8	1.07	136.4
6000.0000	.32	157.7	26.83	177.3		-5.12	83.8	.22	118.8

Measured S-parameters of SSL w=.450 g=.225

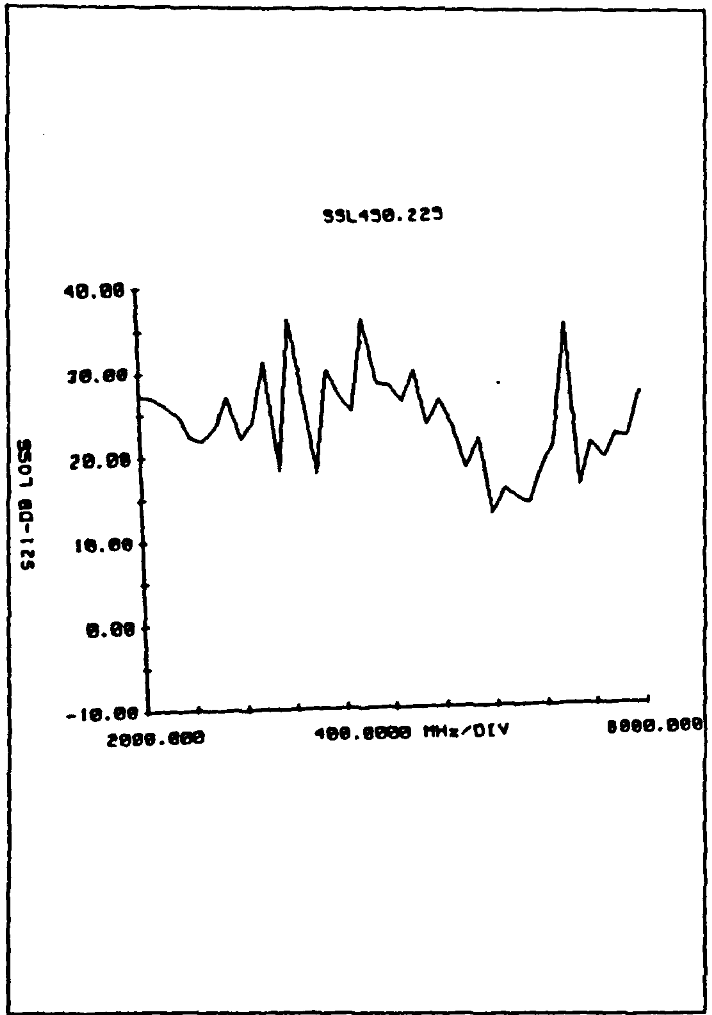


Magnitude S11 v. Frequency

Magnitude S22 v. Frequency

Figure 26. S11,S22 v. Frequency

w = .450" g= .225"



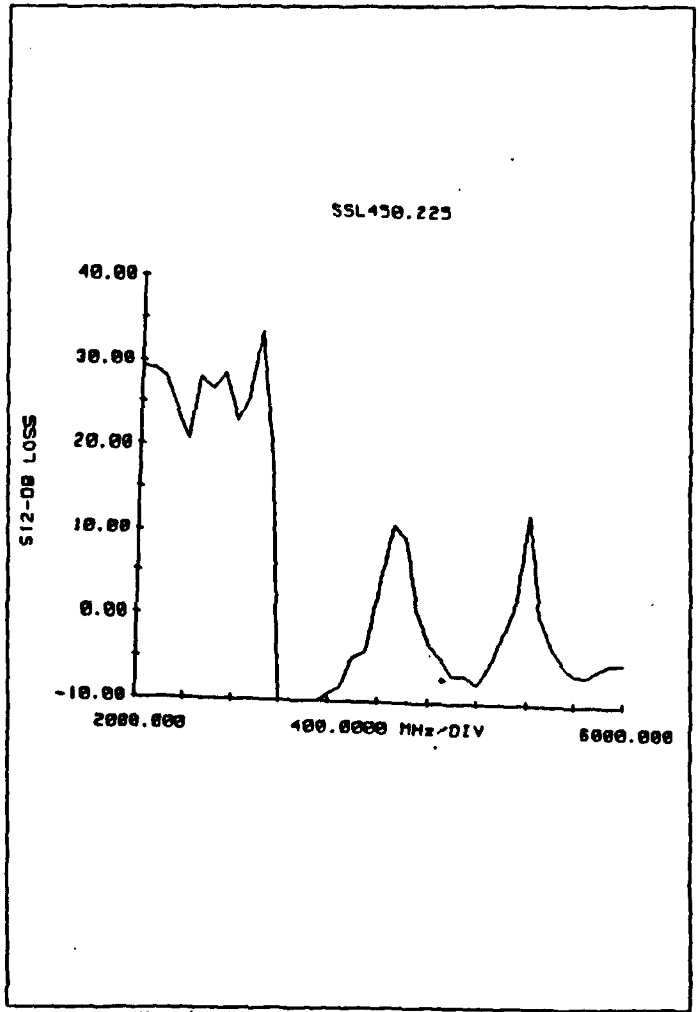


Figure 27. S21,S12 v. Frequency

w = .450" g= .225"

Table 10. MEASURED S-PARAMETERS OF SHIELDED SSL
W= .450" AND G= .150"

SSL450.150

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-OUT S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	.30	-164.7	20.74	-83.9	.0010	22.09	-83.6	.30	168.1
2100.0000	.25	159.9	20.37	-121.0	.0010	21.56	-120.8	.31	133.1
2200.0000	.25	123.0	19.74	-156.4	.0014	21.17	-156.3	.32	100.4
2300.0000	.14	84.3	19.28	153.1	.0008	19.70	147.6	.29	65.8
2400.0000	.17	47.4	18.82	124.8	.0005	18.58	122.2	.23	33.7
2500.0000	1.04	31.9	11.57	105.4	.0006	13.95	108.1	.77	-4.1
2600.0000	.22	-13.4	19.48	82.9	.0021	21.15	82.1	.23	-22.4
2700.0000	.35	-41.6	22.84	6.1	.0006	23.80	6.4	.43	-50.1
2800.0000	.43	-70.0	19.11	-15.8	.0080	19.90	-14.8	.46	-79.1
2900.0000	.36	-94.2	23.17	55.2	.0018	24.57	62.4	.39	-104.2
3000.0000	.34	-119.1	25.81	-10.1	.0009	27.42	-7.0	.30	-130.3
3100.0000	.41	-142.5	16.31	-42.1	.0020	16.96	-37.2	.38	-155.9
3200.0000	.24	-163.6	30.54	-113.4	.0007	30.94	-126.3	.16	-178.5
3300.0000	.16	174.3	24.42	-138.3	.0083	24.46	-146.8	.08	157.0
3400.0000	.11	154.0	17.60	-78.8	.0026	17.89	-67.5	.03	134.1
3500.0000	-.03	131.6	24.96	-172.7	.0023	25.05	-176.8	-.13	108.8
3600.0000	.33	111.0	28.75	105.4	.0073	24.78	94.8	.32	85.2
3700.0000	.35	92.1	23.26	-158.9	.0018	23.28	-140.0	.32	64.9
3800.0000	.30	72.0	27.58	137.4	.0000	27.85	112.4	.32	42.7
3900.0000	.31	49.6	26.11	137.4	.0010	24.63	128.4	.25	21.3
4000.0000	.34	38.3	21.02	101.1	.0010	24.54	124.2	.35	-2.9
4100.0000	.19	16.3	18.55	66.0	.0098	23.63	82.4	3.73	-43.6
4200.0000	.26	-6.6	21.81	74.1	.0010	22.15	68.5	.33	-41.2
4300.0000	.42	-30.0	17.65	38.6	.0006	19.32	41.4	.52	-68.5
4400.0000	.46	-56.1	17.88	15.6	.0013	18.87	14.3	.51	-94.6
4500.0000	.79	-87.4	14.51	-30.1	.0004	15.07	-29.0	.98	-125.4
4600.0000	1.27	-125.2	12.24	-46.1	.0014	13.87	-44.0	1.57	-158.7
4700.0000	2.19	-173.8	12.16	-96.8	.0015	13.58	-98.3	1.63	162.0
4800.0000	2.96	128.7	8.97	-149.3	.0014	9.90	-147.3	1.87	108.3
4900.0000	2.29	52.5	16.08	160.3	.0099	17.15	162.5	1.50	42.0
5000.0000	16.33	-163.8	3.78	162.4	.0038	5.50	159.3	5.73	-26.7
5100.0000	2.53	28.9	13.01	26.0	.0096	14.55	34.0	10.74	33.5
5200.0000	1.53	-25.5	14.09	41.7	.0097	15.27	45.9	1.31	-56.5
5300.0000	1.05	-58.0	18.58	51.7	.0030	21.05	41.8	.51	-95.0
5400.0000	.89	-83.3	30.12	-54.9	.0092	26.33	-59.8	.44	-122.1
5500.0000	.95	-109.9	14.02	-26.3	.0094	15.35	-15.7	.38	-148.0
5600.0000	.97	-131.4	19.28	-4.9	.0043	21.41	9.2	.25	-169.1
5700.0000	1.03	-151.3	18.47	-156.3	.0062	17.46	-146.0	.21	172.9
5800.0000	1.37	-170.9	19.67	-94.2	.0084	20.17	-84.0	.31	153.4
5900.0000	1.36	172.6	20.99	-35.9	.0037	21.64	-13.7	.22	137.5
6000.0000	1.44	155.4	24.61	-168.2		23.39	-165.2	.26	119.6

Measured S-parameters of SSL w=.450 g=.150

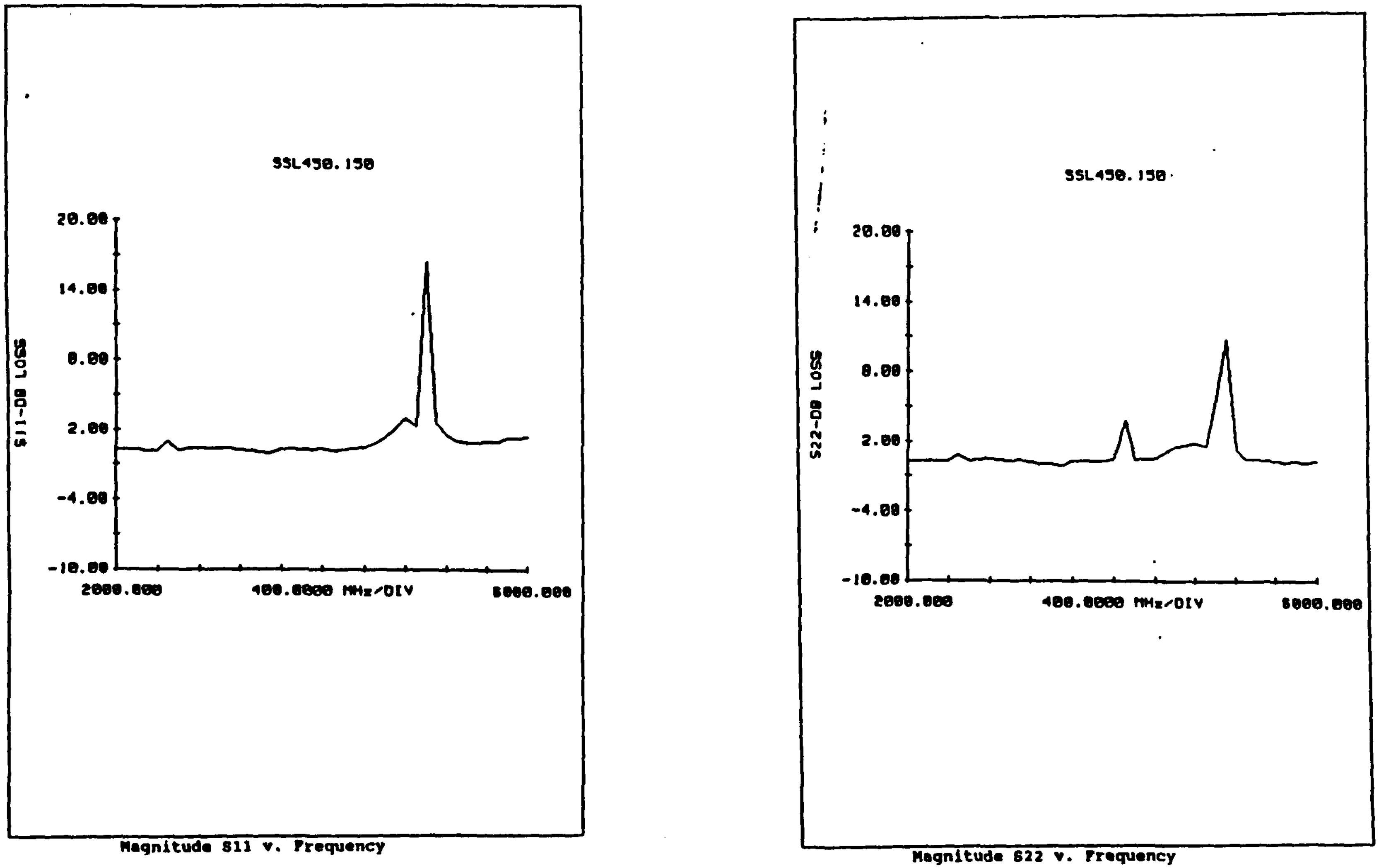
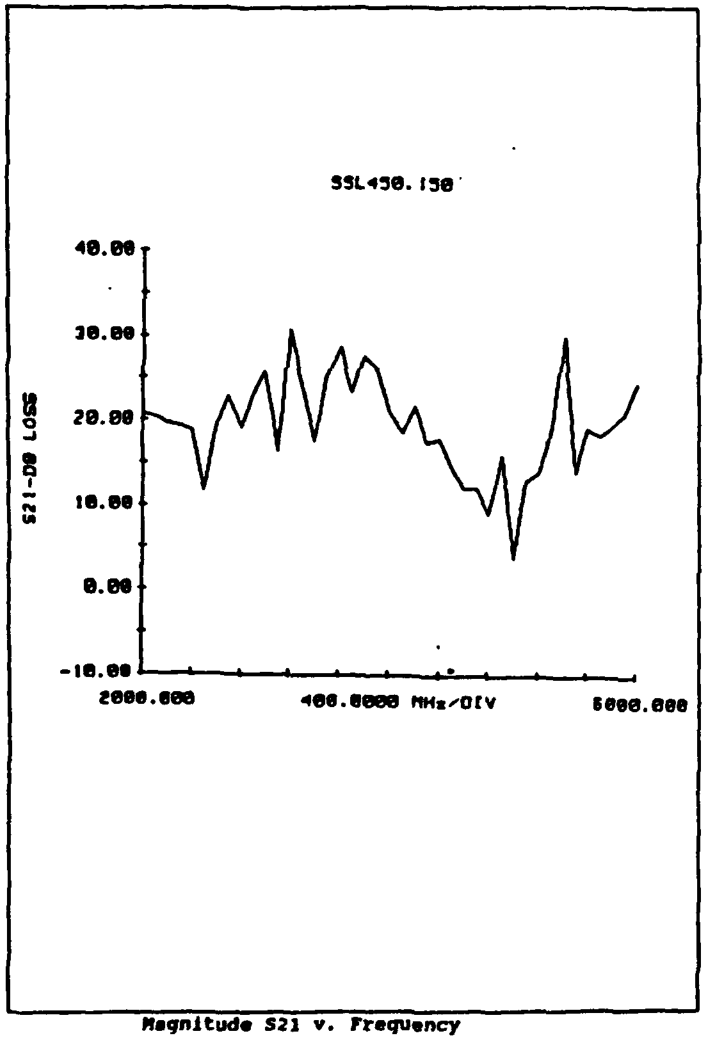


Figure 28. S11,S22 v. Frequency

W = .450" g= .150"



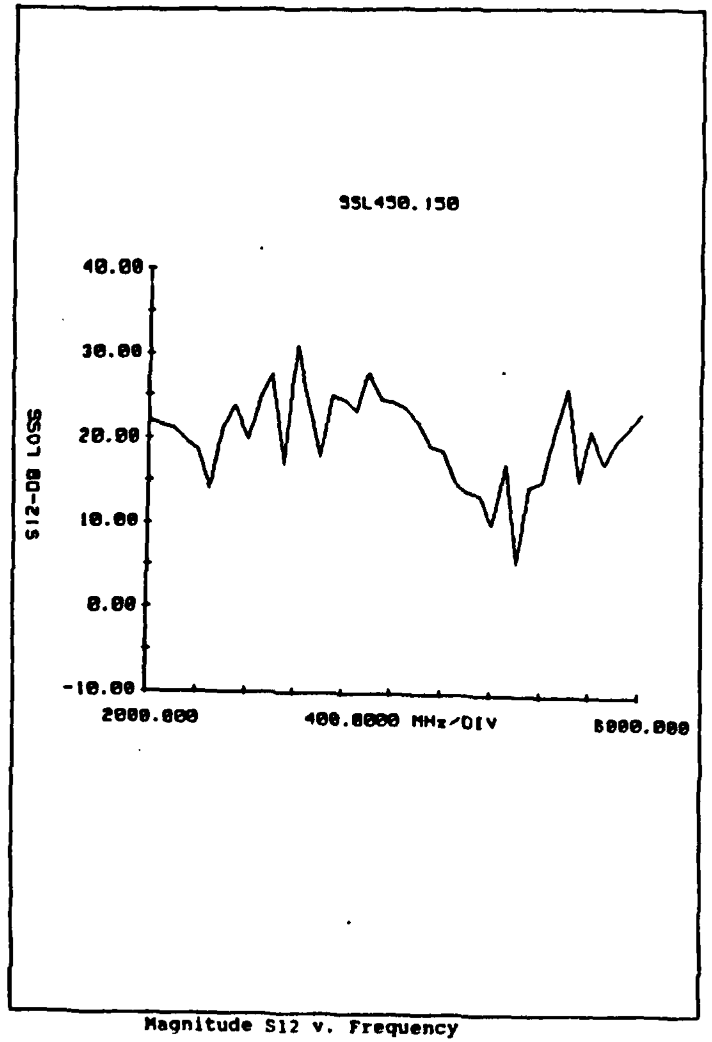


Figure 29. S21,S12 v. Frequency

w = .450" g= .150"

Table 11. MEASURED S-PARAMETERS OF SHIELDED SSL
W= .450" AND G= .1125"

SSL450.1125

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-OUT S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	.42	170.9	11.57	-94.7	.0010	11.80	-15.8	.55	-109.9
2100.0000	.50	135.1	11.11	-131.8	.0010	11.07	-99.5	1.03	-177.1
2200.0000	.49	99.5	10.60	-168.1	.0010	10.80	169.3	.79	98.5
2300.0000	.53	63.4	10.93	155.5	.0010	10.94	173.7	.68	114.1
2400.0000	.49	29.0	10.95	120.4	.0009	11.22	173.7	.75	110.9
2500.0000	.47	-4.5	11.67	89.6	.0009	11.70	79.0	.41	29.4
2600.0000	.45	-35.8	12.41	58.8	.0008	12.51	83.4	.34	-4.6
2700.0000	.46	-63.8	13.49	31.3	.0008	13.73	92.2	.53	-44.8
2800.0000	.38	-91.9	14.47	3.7	.0007	14.83	-1.0	.66	-36.1
2900.0000	.39	-117.8	14.76	-21.9	.0006	15.12	-1.4	.28	-35.6
3000.0000	.32	-143.1	15.59	-42.8	.0006	15.89	4.0	.64	-60.4
3100.0000	.29	-167.2	16.16	-64.2	.0006	16.50	-89.0	.77	-110.4
3200.0000	.26	169.7	16.97	-87.5	.0006	17.14	-85.8	.64	-147.1
3300.0000	.19	147.1	17.78	-106.9	.0007	17.73	-78.5	.57	177.2
3400.0000	.12	125.2	17.77	-133.8	.0007	17.80	-81.6	.54	175.3
3500.0000	.06	101.6	17.60	-157.3	.0006	17.81	-171.0	.33	-171.2
3600.0000	.50	79.4	17.04	-178.3	.0005	17.48	-169.3	.90	-169.7
3700.0000	.49	61.0	16.91	163.5	.0005	16.83	-169.0	.75	107.6
3800.0000	.46	41.1	16.41	146.2	.0006	16.13	-169.2	.49	114.2
3900.0000	.36	20.4	15.26	124.0	.0006	15.32	106.7	.58	26.6
4000.0000	.40	-.2	14.12	102.2	.0006	14.16	107.2	.68	40.1
4100.0000	.47	-22.0	12.20	81.9	.0006	12.36	104.4	.70	42.2
4200.0000	.55	-44.5	10.87	60.2	.0008	10.76	105.5	.86	52.0
4300.0000	.75	-68.7	9.19	32.7	.0009	9.14	112.1	1.02	-36.5
4400.0000	1.18	-93.7	7.01	.0	.0010	7.16	18.9	1.58	-26.8
4500.0000	2.04	-121.2	4.91	-36.8	.0040	5.24	23.3	2.65	-106.4
4600.0000	3.37	-152.5	12.81	177.6	.0041	3.34	20.1	4.53	-105.6
4700.0000	4.98	168.7	13.77	29.0	.0049	1.73	-64.2	5.80	178.1
4800.0000	5.84	121.7	15.07	-148.0	.0025	1.54	-147.5	6.60	98.9
4900.0000	5.77	61.0	15.45	122.0	.0049	2.82	-145.4	6.38	96.5
5000.0000	4.05	.3	13.53	-55.3	.0049	3.27	124.6	4.21	112.5
5100.0000	2.30	-46.7	11.85	129.1	.0027	5.26	130.0	2.45	25.7
5200.0000	1.33	-83.6	11.14	32.1	.0024	7.66	34.3	1.85	19.2
5300.0000	.77	-113.9	10.78	-53.8	.0048	10.47	35.7	.98	-54.2
5400.0000	.60	-138.4	10.07	131.8	.0025	12.64	40.5	.60	-49.1
5500.0000	.55	-160.4	10.10	41.9	.0026	14.37	-44.7	1.16	-43.1
5600.0000	.58	-179.9	10.15	-53.1	.0047	15.57	-43.5	.77	-122.1
5700.0000	.59	162.3	10.86	137.7	.0026	16.47	-50.1	.63	-115.1
5800.0000	.57	145.4	10.24	45.1	.0025	18.96	-47.1	.84	-114.6
5900.0000	.60	129.3	10.14	-44.2	.0023	21.10	-145.0	1.06	164.4
6000.0000	.61	113.2	10.02	-127.1		19.12	-123.1	1.00	175.9

Measured S-parameters of SSL w=.450 g=.1125

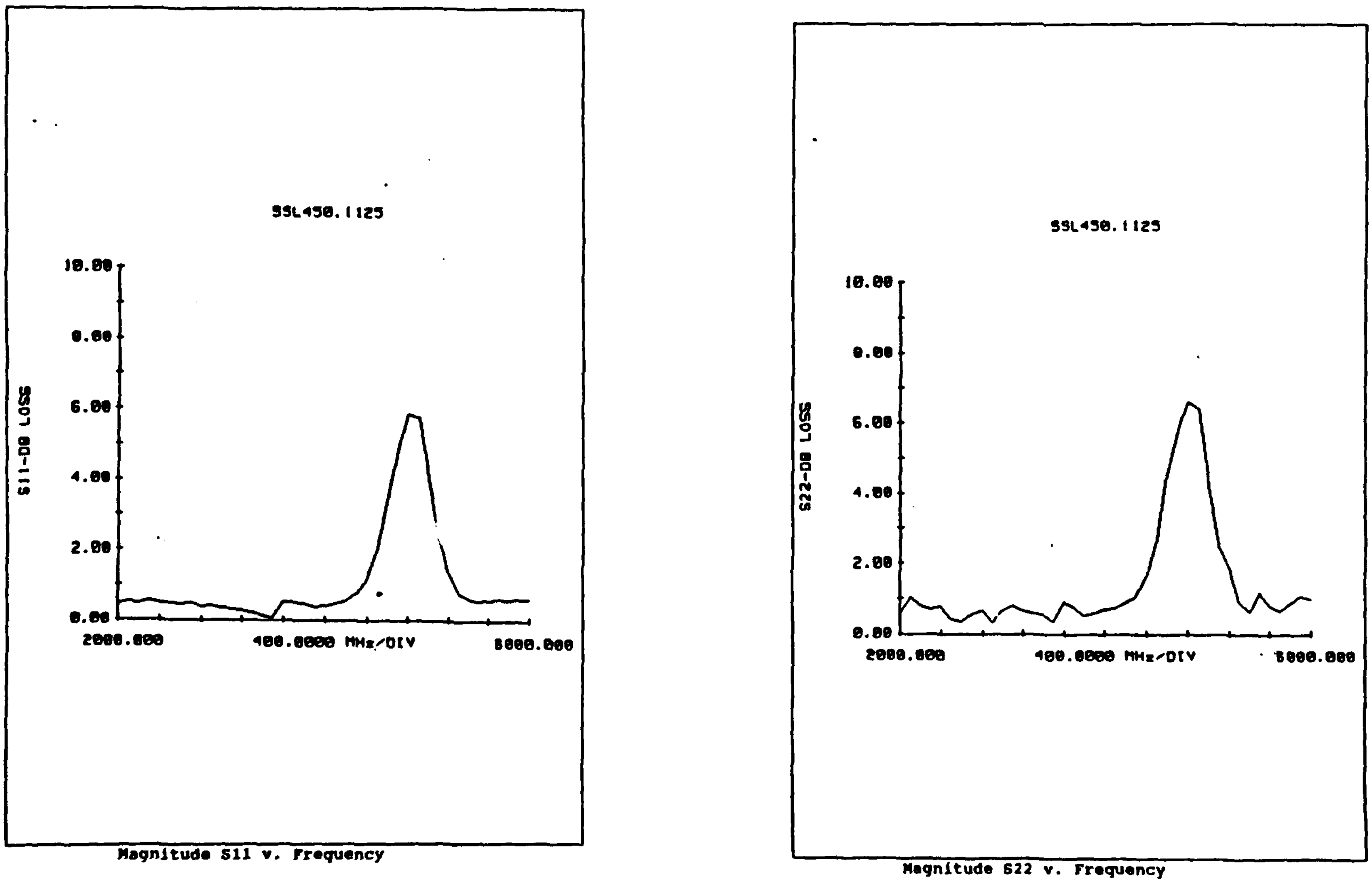


Figure 30. S11,S22 v. Frequency

w = .450" g= .1125"

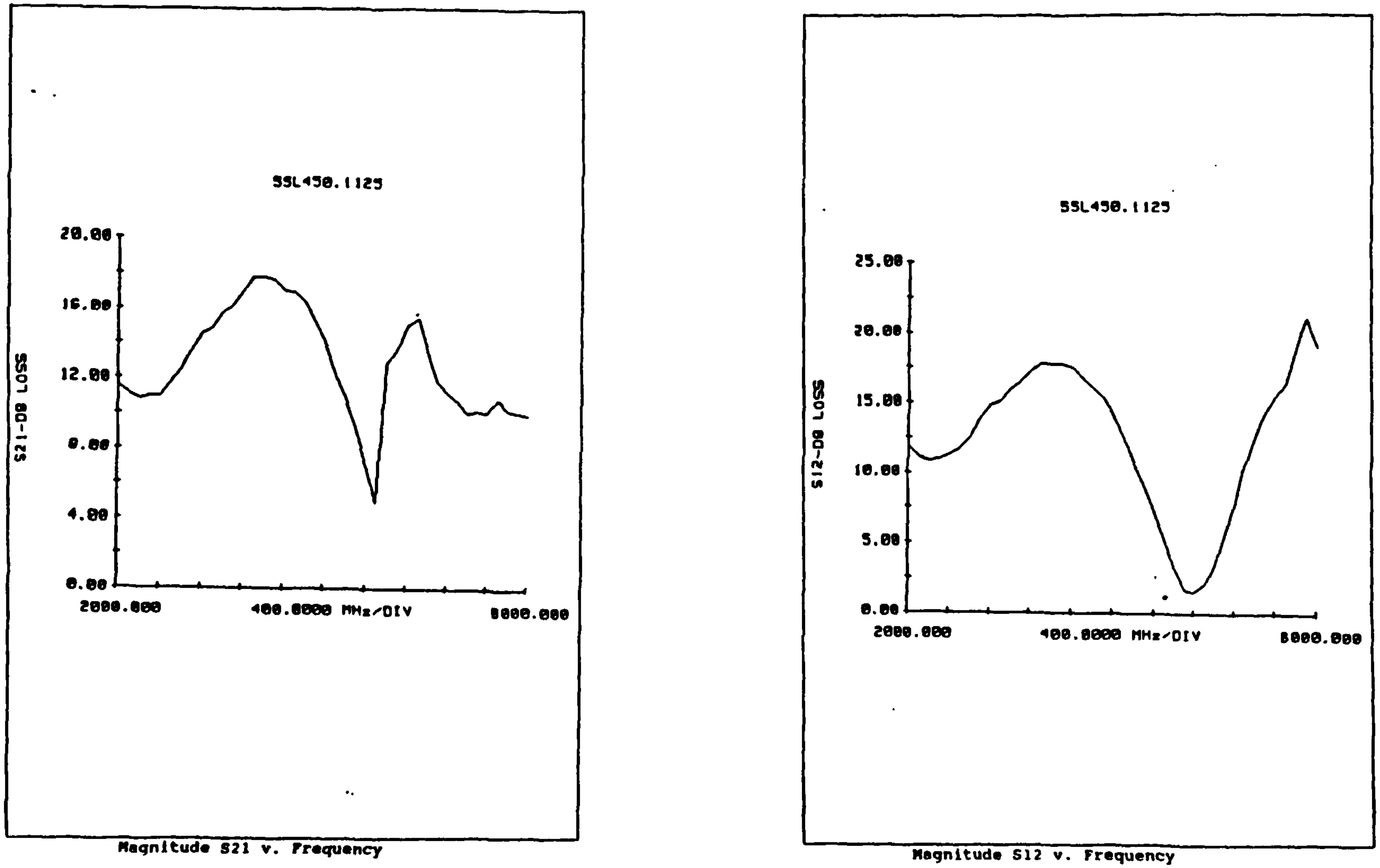


Figure 31. S21,S12 v. Frequency

W = .450" g= .1125"

Table 12. MEASURED S-PARAMETERS OF SHIELDED SSL
W= .300" AND G= .150"

SSL300.150

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-OUT S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	.23	-174.6	3.36	-165.0	.0010	3.42	-165.3	.28	-175.0
2100.0000	.18	154.8	4.01	159.8	.0009	4.05	159.4	.23	156.5
2200.0000	.15	125.3	4.08	128.3	.0007	4.07	128.0	.20	129.3
2300.0000	.17	96.3	3.95	102.4	.0006	4.00	102.3	.22	102.1
2400.0000	.14	69.1	4.24	82.2	.0007	4.24	81.8	.17	76.3
2500.0000	.18	40.9	5.49	55.9	.0007	5.54	55.4	.19	49.6
2600.0000	.21	14.3	5.89	29.1	.0007	5.89	28.1	.21	23.7
2700.0000	.23	-11.3	6.25	4.2	.0007	6.20	3.1	.23	-1.1
2800.0000	.25	-36.1	6.84	-22.1	.0006	6.84	-23.6	.30	-25.7
2900.0000	.32	-60.4	6.66	-44.9	.0006	6.71	-46.5	.36	-49.8
3000.0000	.27	-85.1	7.25	-66.1	.0005	7.25	-67.1	.33	-74.3
3100.0000	.24	-108.0	7.10	-85.5	.0006	7.05	-86.2	.41	-98.0
3200.0000	.34	-132.1	8.25	-108.6	.0008	8.25	-108.6	.41	-122.2
3300.0000	.33	-154.9	8.45	-139.1	.0006	8.41	-138.5	.40	-145.7
3400.0000	.31	-176.6	8.15	-159.6	.0008	8.22	-159.8	.36	-168.5
3500.0000	.26	161.1	8.41	171.9	.0007	8.45	171.6	.31	167.9
3600.0000	.46	139.0	7.15	148.3	.0005	7.15	147.8	.48	144.2
3700.0000	.49	118.7	6.55	129.0	.0006	6.49	128.5	.48	121.8
3800.0000	.48	97.7	6.97	109.1	.0007	6.90	108.6	.48	98.7
3900.0000	.36	76.4	6.19	84.0	.0007	6.13	83.2	.40	75.3
4000.0000	.43	54.4	5.65	59.1	.0007	5.55	58.3	.42	51.1
4100.0000	.38	31.8	5.20	35.1	.0007	5.15	34.2	.38	26.3
4200.0000	.47	7.0	4.40	9.3	.0007	4.35	7.8	.45	-.4
4300.0000	.57	-19.9	3.51	-16.6	.0007	3.45	-18.4	.54	-28.9
4400.0000	.72	-49.6	2.55	-43.4	.0009	2.60	-44.7	.59	-58.5
4500.0000	1.06	-82.9	2.65	-75.3	.0009	2.72	-77.0	.77	-90.9
4600.0000	1.32	-118.8	1.70	-108.5	.0044	1.70	-109.8	.89	-123.5
4700.0000	1.60	-158.1	-1.81	93.5	.0083	-1.85	93.1	.95	-157.7
4800.0000	1.83	161.9	-1.65	153.2	.0082	-1.75	153.1	1.01	168.5
4900.0000	1.76	119.1	-2.20	-141.6	.0084	-2.30	-143.0	.81	132.6
5000.0000	2.29	86.3	-1.43	-83.9	.0081	-1.58	-86.1	.99	105.1
5100.0000	2.52	57.9	-1.70	-15.1	.0082	-1.96	-19.6	1.01	76.1
5200.0000	2.58	30.4	-1.35	50.3	.0080	-1.45	44.7	1.13	46.9
5300.0000	2.29	7.0	.75	122.4	.0082	.75	116.7	.86	23.0
5400.0000	1.77	-16.4	-.19	-171.3	.0082	.01	-177.1	.65	-3.2
5500.0000	1.29	-40.8	1.00	-108.0	.0080	1.30	-112.1	.55	-28.1
5600.0000	.98	-64.7	2.09	-34.4	.0083	2.31	-35.5	.49	-52.2
5700.0000	.80	-89.0	1.95	28.4	.0079	2.21	27.5	.48	-76.7
5800.0000	.63	-112.6	4.40	104.2	.0081	4.69	104.4	.42	-100.9
5900.0000	.58	-135.6	4.47	171.8	.0081	4.61	172.2	.44	-125.5
6000.0000	.61	-157.0	3.95	-119.3		4.09	-119.1	.50	-148.5

Measured S-parameters of SSL w=.300 g=.150

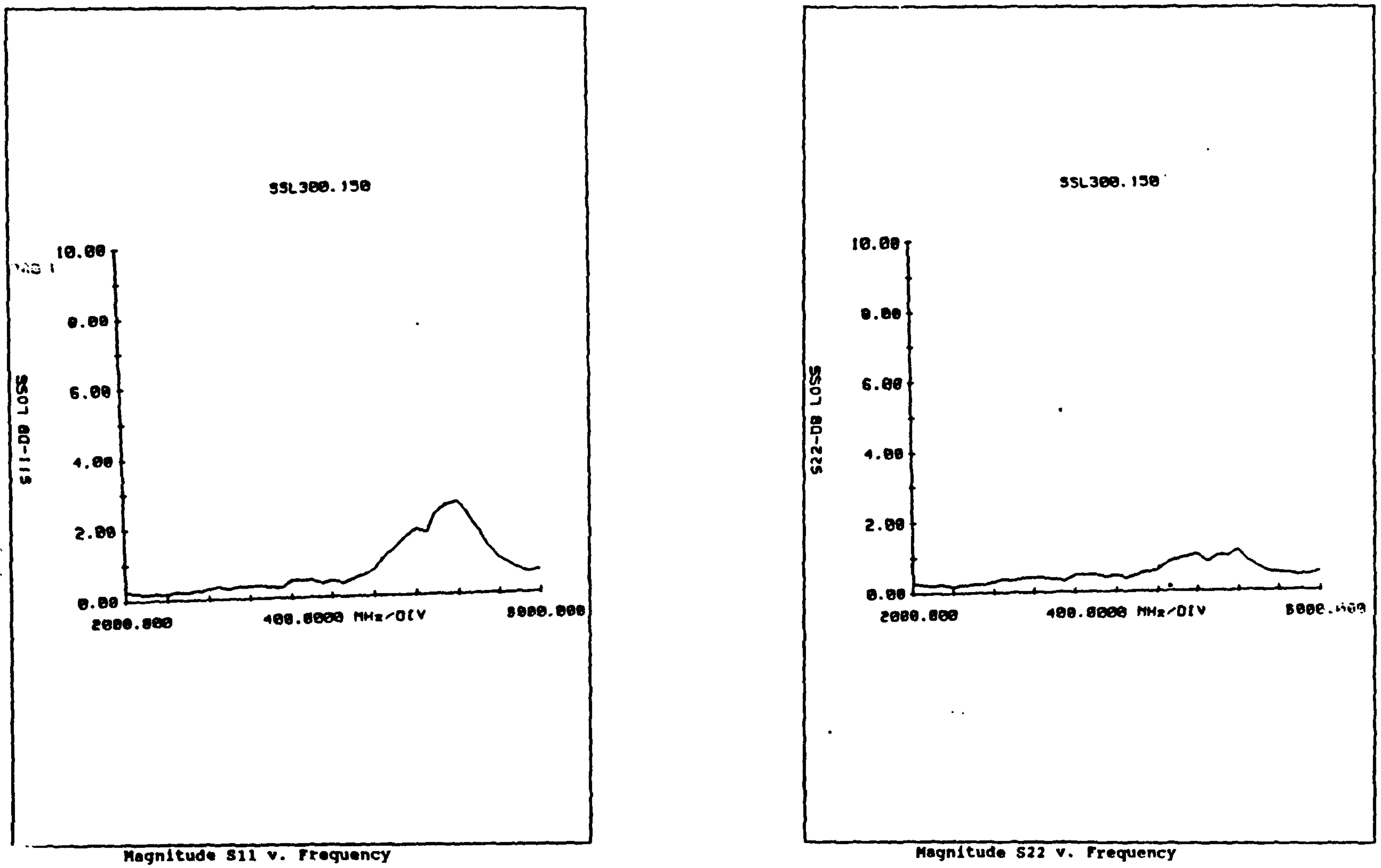


Figure 32. S11,S22 v. Frequency

w = .300" g= .150"

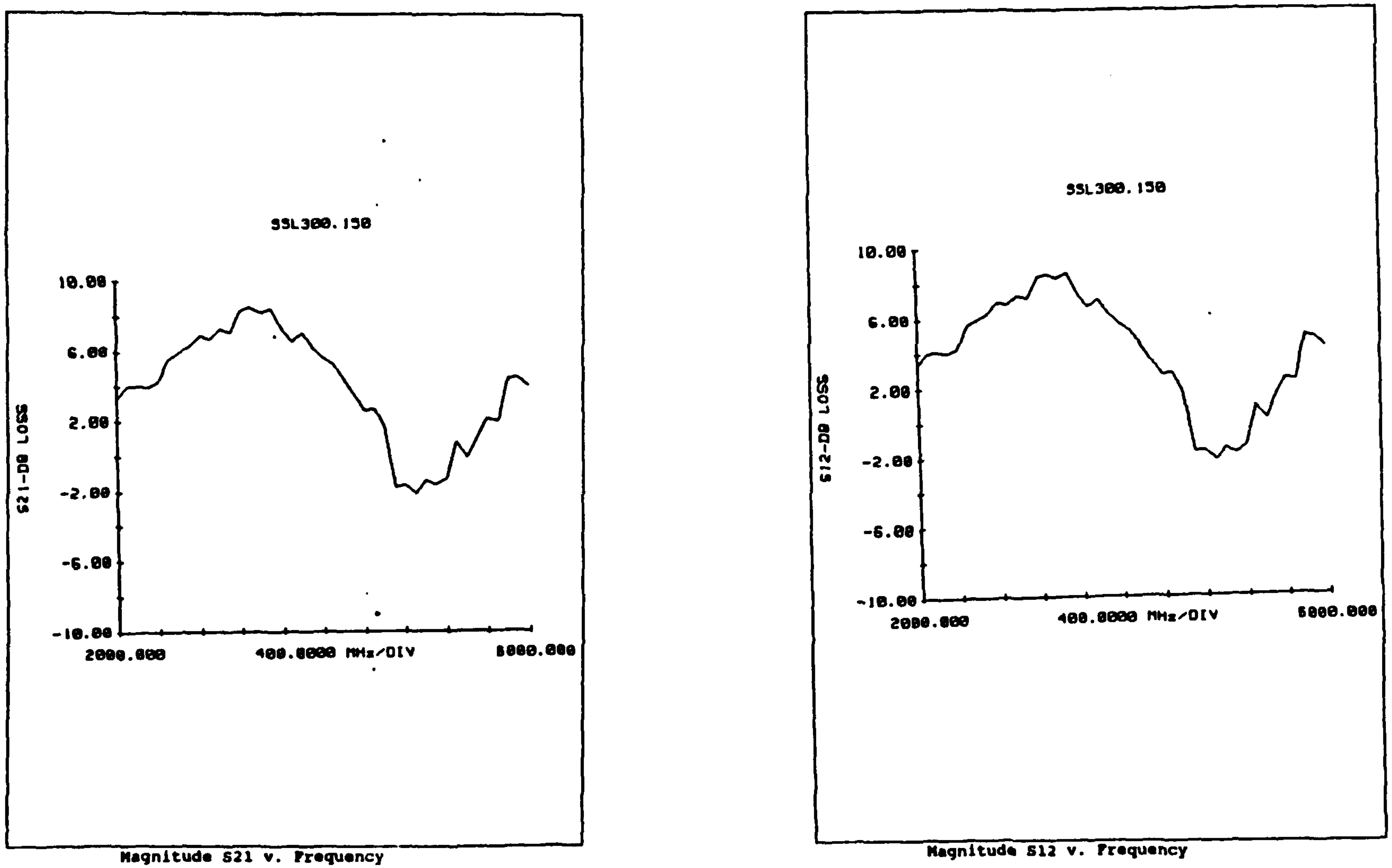


Figure 33. S21,S12 v. Frequency

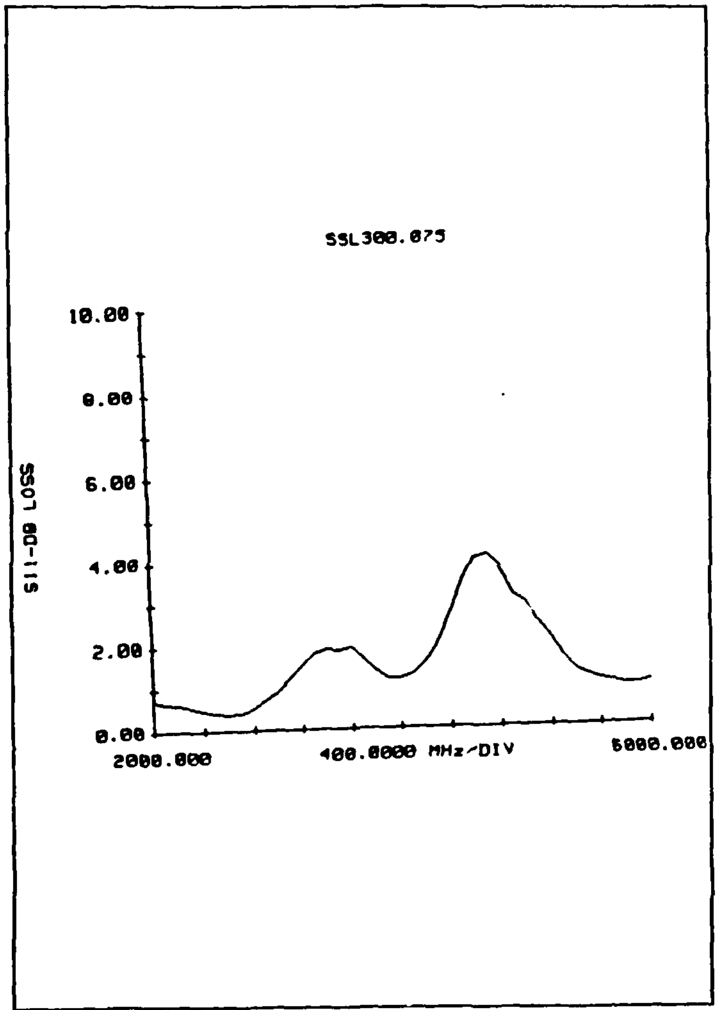
w = .300" g= .150"

Table 13. MEASURED S-PARAMETERS OF SHIELDED SSL
W= .300" AND G= .075"

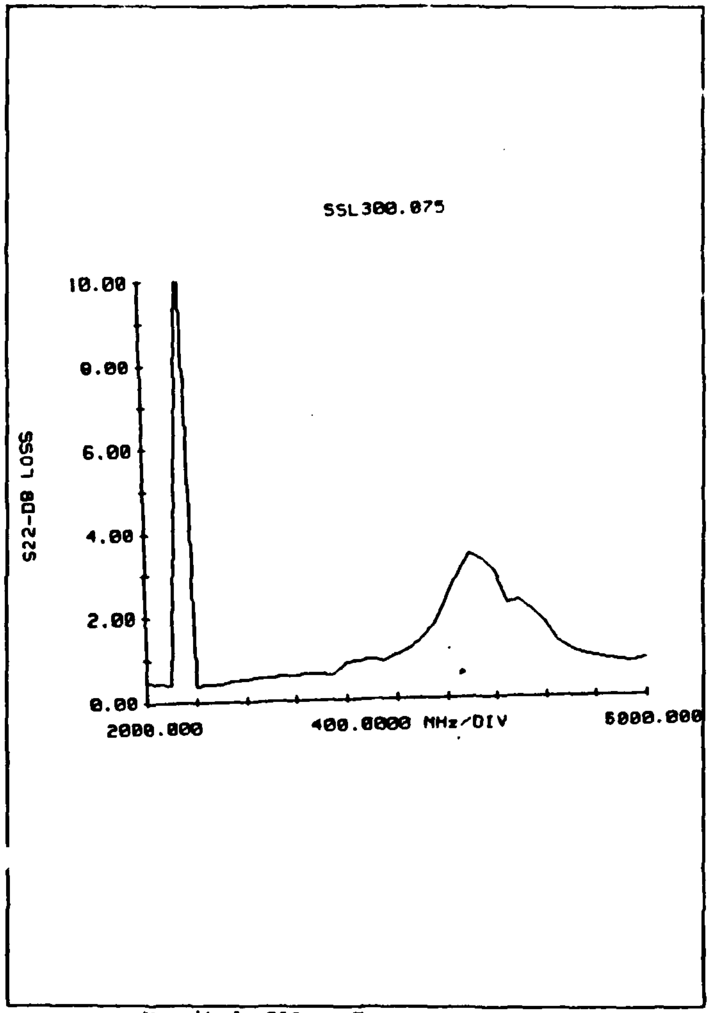
SSL300.075

FREQUENCY MHz	RETURN LOSS-IN S11 DB	RETURN LOSS-IN S11 ANG	LOSS-FORWARD S21 DB	LOSS-FORWARD S21 ANG	DELAY u-SEC	LOSS-REVERSE S12 DB	LOSS-REVERSE S12 ANG	RETURN LOSS-OUT S22 DB	RETURN LOSS-OUT S22 ANG
2000.0000	.70	172.8	-2.80	-178.6	.0010	-4.46	176.8	.46	168.4
2100.0000	.65	143.8	-1.95	146.8	.0009	-3.50	-137.1	.42	137.6
2200.0000	.60	116.3	-1.75	115.4	.0007	-3.96	96.3	.39	108.5
2300.0000	.54	89.1	-1.70	88.9	.0006	-3.70	-27.1	11.37	82.4
2400.0000	.46	63.5	-1.40	68.3	.0007	-3.20	-141.1	.38	52.5
2500.0000	.40	36.6	-.21	42.3	.0008	-2.56	95.8	.40	25.0
2600.0000	.38	10.8	.14	15.3	.0007	-2.14	-27.4	.41	-.8
2700.0000	.41	-14.4	.55	-9.8	.0008	-1.60	-145.0	.45	-25.1
2800.0000	.49	-39.4	1.19	-36.8	.0007	-1.36	94.5	.49	-49.1
2900.0000	.70	-64.5	.81	-60.7	.0006	-1.50	-26.5	.54	-72.5
3000.0000	.89	-90.3	1.43	-80.9	.0006	-1.25	-140.0	.52	-96.3
3100.0000	1.25	-115.0	1.20	-100.9	.0006	-1.64	104.2	.58	-119.0
3200.0000	1.51	-139.3	2.65	-122.7	.0008	-.40	-12.0	.59	-141.6
3300.0000	1.7[illegible]	-152.4	3.30	-1[illegible]1.9	.0005	.90	-132.7	.62	-163.4
3400.0000	1.89	175.5	2.63	-172.6	.0008	0.00	115.9	.61	175.2
3500.0000	1.85	152.6	2.85	160.4	.0006	.95	-6.5	.59	152.4
3600.0000	1.93	129.8	1.35	137.0	.0006	.36	-121.4	.86	129.9
3700.0000	1.64	106.1	.40	116.8	.0006	.10	124.5	.89	109.2
3800.0000	1.39	84.2	.35	96.0	.0008	1.10	7.8	.93	87.0
3900.0000	1.16	59.5	-.61	68.7	.0008	1.48	-107.0	.98	64.2
4000.0000	1.16	33.6	-1.35	41.4	.0008	1.45	131.3	1.02	39.9
4100.0000	1.27	6.3	-1.90	13.6	.0008	2.60	7.9	1.17	13.8
4200.0000	1.54	-23.1	-2.80	-15.9	.0008	2.40	-116.0	1.40	-15.4
4300.0000	1.97	-53.2	-3.57	-44.3	.0008	2.50	120.2	1.73	-46.6
4400.0000	2.65	-84.7	-4.25	-72.5	.0009	3.25	-7.5	2.33	-81.1
4500.0000	3.39	-118.6	-3.50	-105.7	.0010	5.05	-140.6	2.95	-119.9
4600.0000	3.99	-152.7	-3.90	-140.5	.0044	5.45	83.2	3.39	-160.9
4700.0000	4.09	172.3	-6.96	62.7	.0083	2.00	-179.1	3.24	157.3
4800.0000	3.80	141.4	-6.40	124.0	.0082	2.45	144.3	2.98	120.8
4900.0000	3.10	107.0	-6.64	-172.8	.0084	2.05	117.9	2.21	83.0
5000.0000	2.95	83.4	-5.83	-114.1	.0082	1.52	80.5	2.29	57.0
5100.0000	2.47	57.2	-5.85	-49.1	.0082	1.34	54.9	2.09	29.7
5200.0000	2.08	29.6	-5.40	16.0	.0080	.65	32.6	1.74	3.7
5300.0000	1.62	4.8	-3.65	88.1	.0081	.50	7.2	1.31	-20.6
5400.0000	1.30	-19.9	-3.69	155.2	.0081	.22	-15.3	1.10	-42.7
5500.0000	1.17	-43.8	-2.15	-137.2	.0078	.35	-37.2	.98	-65.2
5600.0000	1.06	-67.2	-.09	-56.7	.0003	-.16	-59.4	.91	-86.6
5700.0000	.99	-91.2	.00	-66.1	.0004	-.11	-85.2	.84	-108.6
5800.0000	.94	-115.9	-.10	-81.6	.0009	-.15	-96.3	.82	-130.7
5900.0000	.91	-140.3	-.13	-115.3	.0006	-.26	-126.2	.77	-151.8
6000.0000	.98	-163.8	.27	-136.5		.20	-145.6	.85	-172.3

Measured S-parameters of SSL w=.300 g=.075



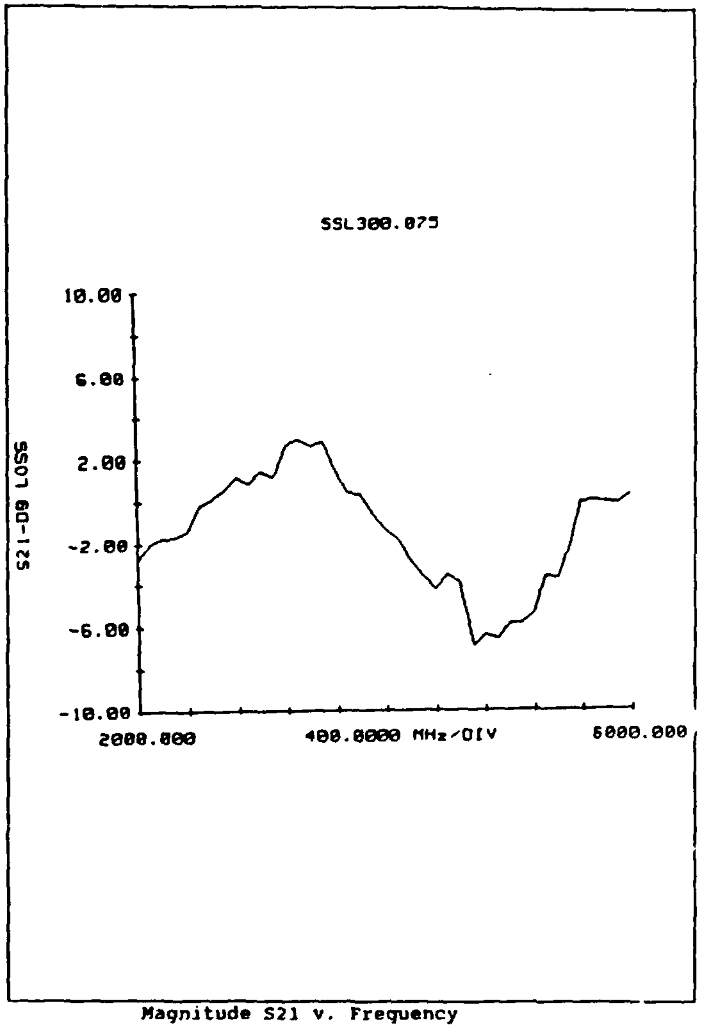
Magnitude S11 v. Frequency



Magnitude S22 v. Frequency

Figure 34. S11,S22 v. Frequency

w = .300" g= .075"



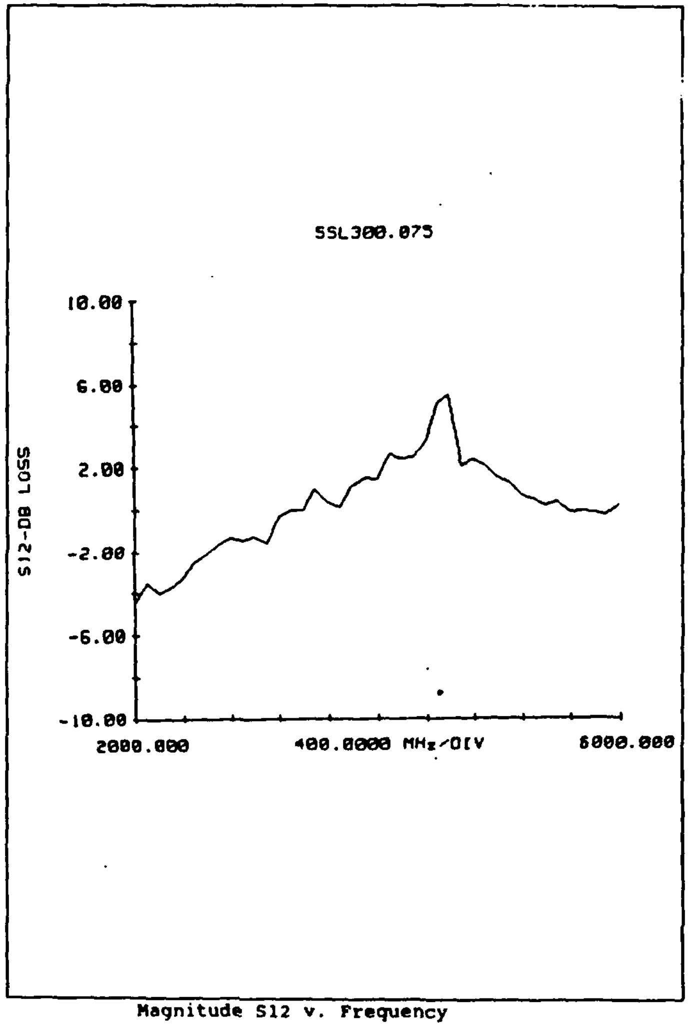


Figure 35. S21,S12 v. Frequency

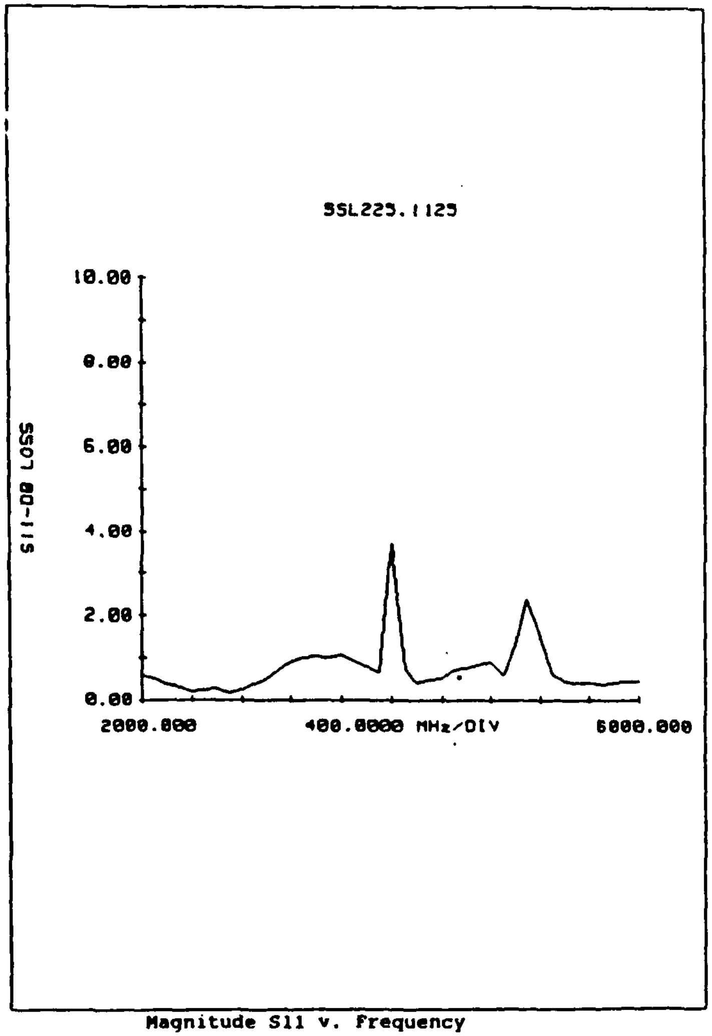
w = .300" g= .075"

Table 14. MEASURED S-PARAMETERS OF SHIELDED SSL
W= .225" AND G= .1125"

SSL225.1125

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-OUT S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	.57	157.3	19.55	-96.7	.0004	13.90	-103.2	.29	160.9
2100.0000	.50	130.0	19.21	-112.4	.0003	12.96	-121.9	.21	132.6
2200.0000	.38	105.0	18.17	-124.3	.0004	11.58	-135.8	.18	106.4
2300.0000	.29	80.8	15.91	-139.6	.0003	8.85	-154.4	.14	80.7
2400.0000	.20	56.2	12.10	-151.6	.0007	4.24	-177.6	.17	56.7
2500.0000	.22	33.8	4.44	-176.1	.0041	-2.06	110.0	.47	33.7
2600.0000	.25	16.1	2.59	37.0	.0008	4.44	31.8	.22	11.8
2700.0000	.15	-6.9	11.77	9.2	.0004	9.55	7.5	.18	-10.4
2800.0000	.21	-28.4	15.98	-5.7	.0003	12.55	-9.8	.20	-32.2
2900.0000	.36	-49.8	18.10	-17.2	.0004	14.14	-22.8	.26	-53.0
3000.0000	.48	-72.3	19.66	-29.9	.0003	15.29	-36.3	.28	-76.2
3100.0000	.72	-93.9	20.35	-40.6	.0004	15.83	-47.0	.36	-98.0
3200.0000	.87	-116.9	20.69	-53.4	.0004	15.95	-62.2	.36	-121.1
3300.0000	1.00	-140.1	19.39	-69.2	.0001	14.96	-81.3	.47	-144.5
3400.0000	1.02	-163.6	19.39	-74.1	.0004	-.20	-87.9	.35	-167.2
3500.0000	.99	171.1	18.50	-88.9	.0004	.74	8.2	.31	167.9
3600.0000	1.06	144.2	16.01	-104.8	.0604	.00	-110.3	.49	141.6
3700.0000	.94	117.4	13.64	-118.9	.0004	-.20	131.4	.59	116.0
3800.0000	.78	88.2	9.78	-133.6	.0007	.90	9.1	.73	88.2
3900.0000	.66	56.1	4.03	-158.6	.0021	1.73	-111.1	1.15	60.0
4000.0000	3.71	26.2	-6.05	124.9	.0026	1.90	128.8	1.47	37.4
4100.0000	.71	10.8	1.21	31.8	.0008	2.25	2.3	.82	8.2
4200.0000	.40	-23.3	6.18	2.8	.0006	1.55	-125.7	.55	-24.9
4300.0000	.48	-55.6	8.70	-17.4	.0004	1.26	105.9	.54	-60.8
4400.0000	.51	-86.4	10.05	-32.8	.0006	1.45	-22.6	.55	-96.9
4500.0000	.72	-116.7	11.16	-53.7	.0005	2.00	-154.6	.69	-133.7
4600.0000	.76	-147.1	10.65	-72.6	.0039	2.80	73.1	.75	-170.2
4700.0000	.80	-178.3	6.34	148.6	.0003	-.36	179.2	.86	155.6
4800.0000	.89	149.7	.45	-149.0	.0018	.20	146.6	.75	122.5
4900.0000	.57	113.5	.24	147.9	.0011	.06	121.9	.26	87.3
5000.0000	1.31	85.6	.62	107.5	.0007	.28	85.8	.96	62.5
5100.0000	2.37	57.6	1.65	83.1	.0004	.85	64.0	1.60	38.9
5200.0000	1.47	37.5	.20	67.1	.0010	-.15	47.8	1.04	18.6
5300.0000	.62	5.5	-.09	32.3	.0008	-.17	21.6	.54	-5.7
5400.0000	.43	-25.3	-.48	3.0	.0008	-.43	-1.4	.48	-29.4
5500.0000	.39	-54.1	-.39	-26.0	.0008	-.25	-23.9	.50	-52.1
5600.0000	.39	-81.4	-.70	-54.2	.0008	-.56	-46.7	.53	-73.9
5700.0000	.38	-106.1	-.65	-84.4	.0004	-.40	-71.8	.58	-96.4
5800.0000	.40	-133.6	-.55	-99.2	.0009	-.25	-84.6	.73	-118.5
5900.0000	.43	-157.6	-.64	-131.6	.0006	-.13	-114.7	.85	-139.9
6000.0000	.45	-178.5	-.20	-152.2		.30	-134.3	.94	-161.2

Measured S-parameters of SSL w=.225 g=.1125



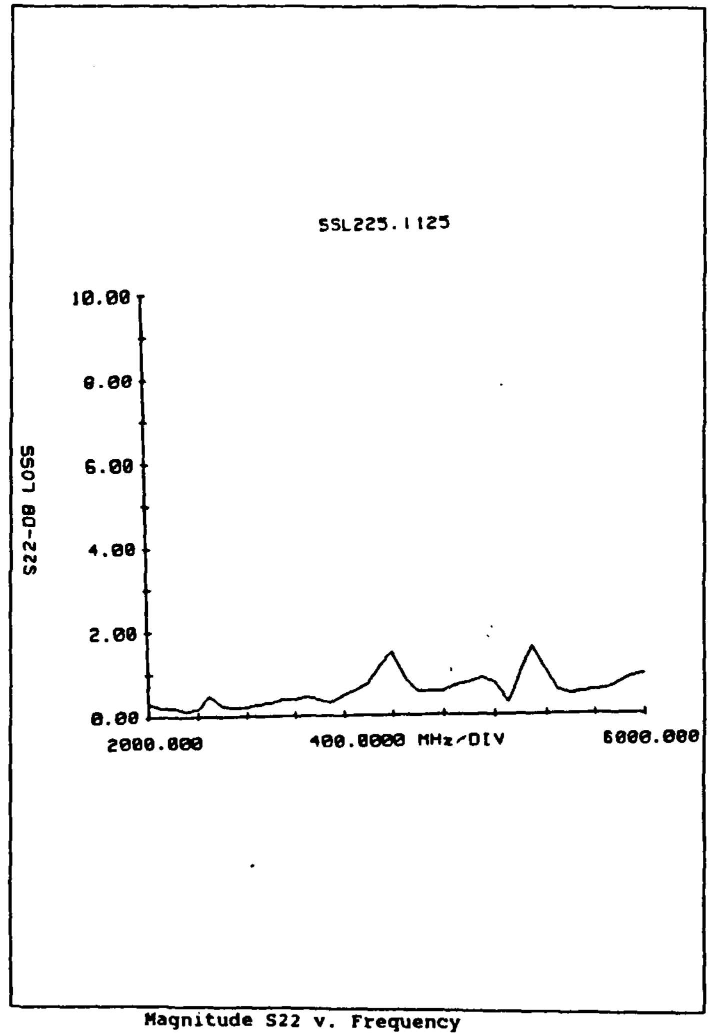


Figure 36. S11,S22 v. Frequency

w = .225" g= .1125"

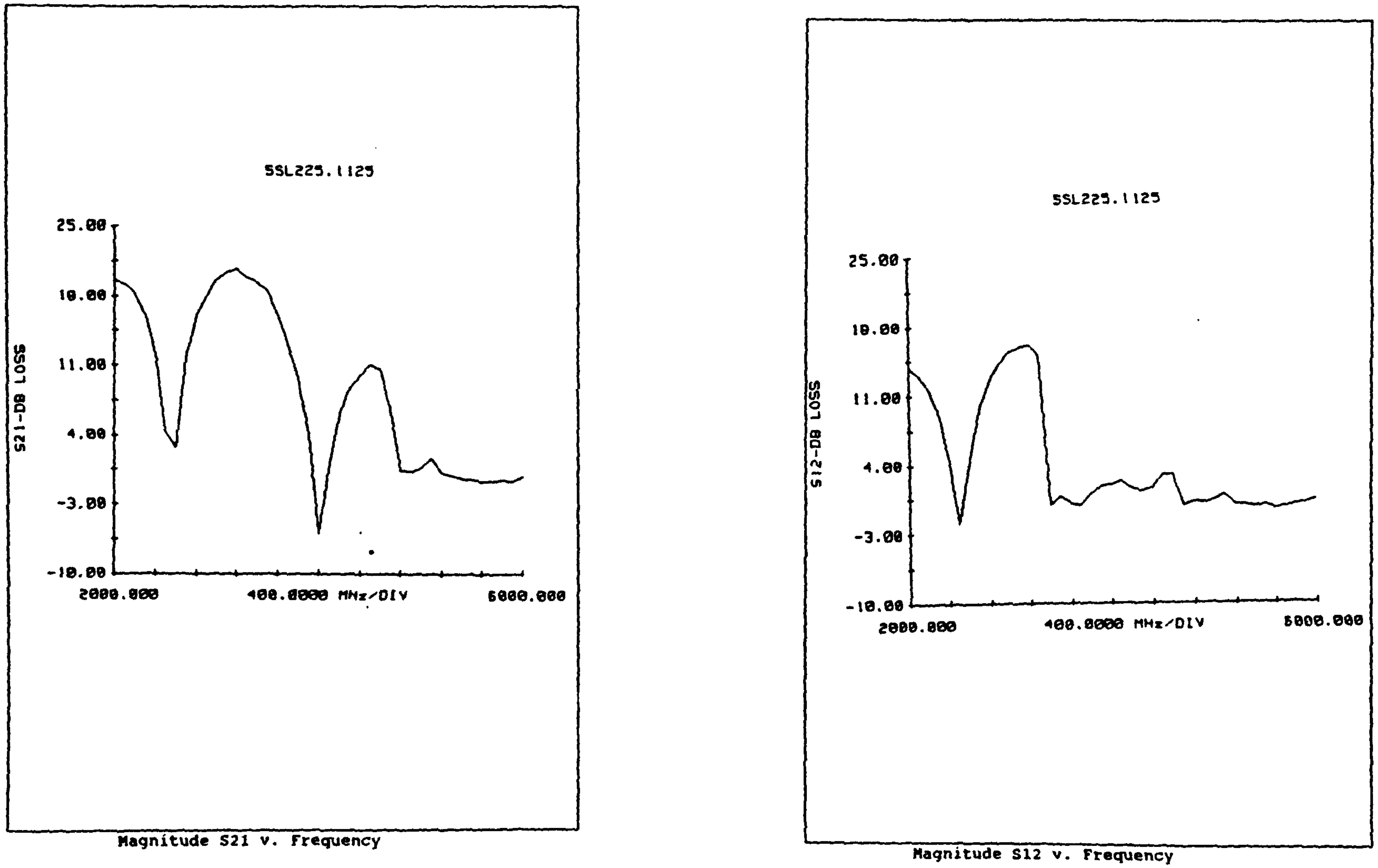


Figure 37. S21,S12 v. Frequency

W = .225" g= .1125"

Table 15. MEASURED S-PARAMETERS OF SHIELDED SSL W= .225" AND G= .075"

SSL225.075

FREQUENCY MHz	RETURN LOSS-IN S11 DB	S11 ANG	LOSS-FORWARD S21 DB	S21 ANG	DELAY u-SEC	LOSS-REVERSE S12 DB	S12 ANG	RETURN LOSS-OUT S22 DB	S22 ANG
2000.0000	.30	168.6	1.00	169.8	.0009	1.34	163.0	.49	135.5
2100.0000	.23	140.0	2.35	137.8	.0008	2.75	131.7	.48	108.2
2200.0000	.19	113.2	2.97	108.7	.0007	3.34	104.4	.41	83.7
2300.0000	.18	87.4	3.24	-84.4	.0005	3.75	81.4	.39	59.0
2400.0000	.17	63.6	3.70	56.4	.0006	4.05	63.6	.39	36.2
2500.0000	.19	39.4	4.96	43.3	.0007	5.04	41.2	.44	13.1
2600.0000	.20	16.6	5.39	19.4	.0006	5.39	18.0	.52	-9.8
2700.0000	.21	-5.2	5.68	-2.6	.0007	5.80	-4.4	.67	-31.2
2800.0000	.26	-26.2	6.10	-26.4	.0006	6.04	-29.3	.85	-53.7
2900.0000	.30	-47.1	5.73	-46.9	.0005	5.65	-50.4	1.10	-75.7
3000.0000	.29	-68.5	5.95	-65.4	.0005	6.01	-70.6	1.29	-99.1
3100.0000	.37	-89.5	5.36	-83.0	.0006	5.65	-88.9	1.54	-122.2
3200.0000	.38	-111.8	6.05	-103.7	.0008	6.47	-110.7	1.71	-145.3
3300.0000	.46	-134.0	5.65	-132.6	.0006	6.28	-141.2	1.71	-168.9
3400.0000	.66	-155.7	5.20	-154.9	.0008	5.55	-161.9	1.63	167.4
3500.0000	.53	-177.7	4.82	177.7	.0007	5.25	173.2	1.40	140.5
3600.0000	.60	157.5	2.70	153.0	.0006	3.53	149.2	1.49	113.0
3700.0000	.69	133.1	1.49	131.0	.0007	2.20	127.3	1.21	86.8
3800.0000	.77	107.7	1.34	106.6	.0055	1.85	104.3	.96	57.8
3900.0000	.80	80.9	1.34	-90.0	.0035	.48	76.1	.79	28.0
4000.0000	.94	53.2	1.35	144.3	.0035	-.29	46.7	.85	-3.4
4100.0000	1.02	24.0	2.45	18.2	.0035	-.69	16.1	1.89	-35.9
4200.0000	1.10	-7.2	2.15	-107.6	.0035	-1.50	-20.0	1.44	-68.2
4300.0000	1.31	-39.6	2.01	127.1	.0035	-2.23	-53.2	2.07	-100.6
4400.0000	1.45	-73.2	2.40	.7	.0036	-2.64	-83.0	2.60	-132.9
4500.0000	1.65	-108.3	3.70	-129.2	.0036	-1.14	-118.5	3.03	-166.7
4600.0000	1.70	-143.9	3.65	100.4	.0071	-.75	-154.5	3.22	159.9
4700.0000	1.71	179.5	.46	-156.8	.0009	-3.35	48.1	2.84	127.0
4800.0000	1.81	145.6	1.38	169.7	.0006	-2.10	111.9	2.45	93.7
4900.0000	1.76	113.4	1.40	148.0	.0010	-2.15	-177.1	1.58	57.2
5000.0000	1.38	91.2	.72	112.6	.0007	-1.61	-114.1	1.73	29.5
5100.0000	1.01	63.1	.25	89.1	.0007	-1.58	-43.4	1.42	-.4
5200.0000	.61	35.2	-.45	64.7	.0009	-1.54	24.5	1.16	-28.5
5300.0000	.64	10.1	.00	36.7	.0006	.35	97.2	.92	-54.9
5400.0000	.58	-13.9	-.36	15.1	.0007	.02	167.0	.89	-79.0
5500.0000	.49	-36.6	-.40	-8.4	.0006	1.26	-126.1	.78	-103.7
5600.0000	.18	-56.9	-.61	-30.9	.0007	2.20	-52.2	.74	-126.7
5700.0000	.48	-81.5	-.50	-55.3	.0004	1.68	11.7	.78	-148.7
5800.0000	.53	-103.8	-.50	-78.5	.0008	3.10	89.7	.76	-170.3
5900.0000	.59	-126.1	-.34	-100.7	.0006	2.90	159.5	.82	169.8
6000.0000	.70	-148.0	-.05	-120.6		2.64	-132.0	.89	150.6

Measured S-parameters of SSL w=.225 g=.075

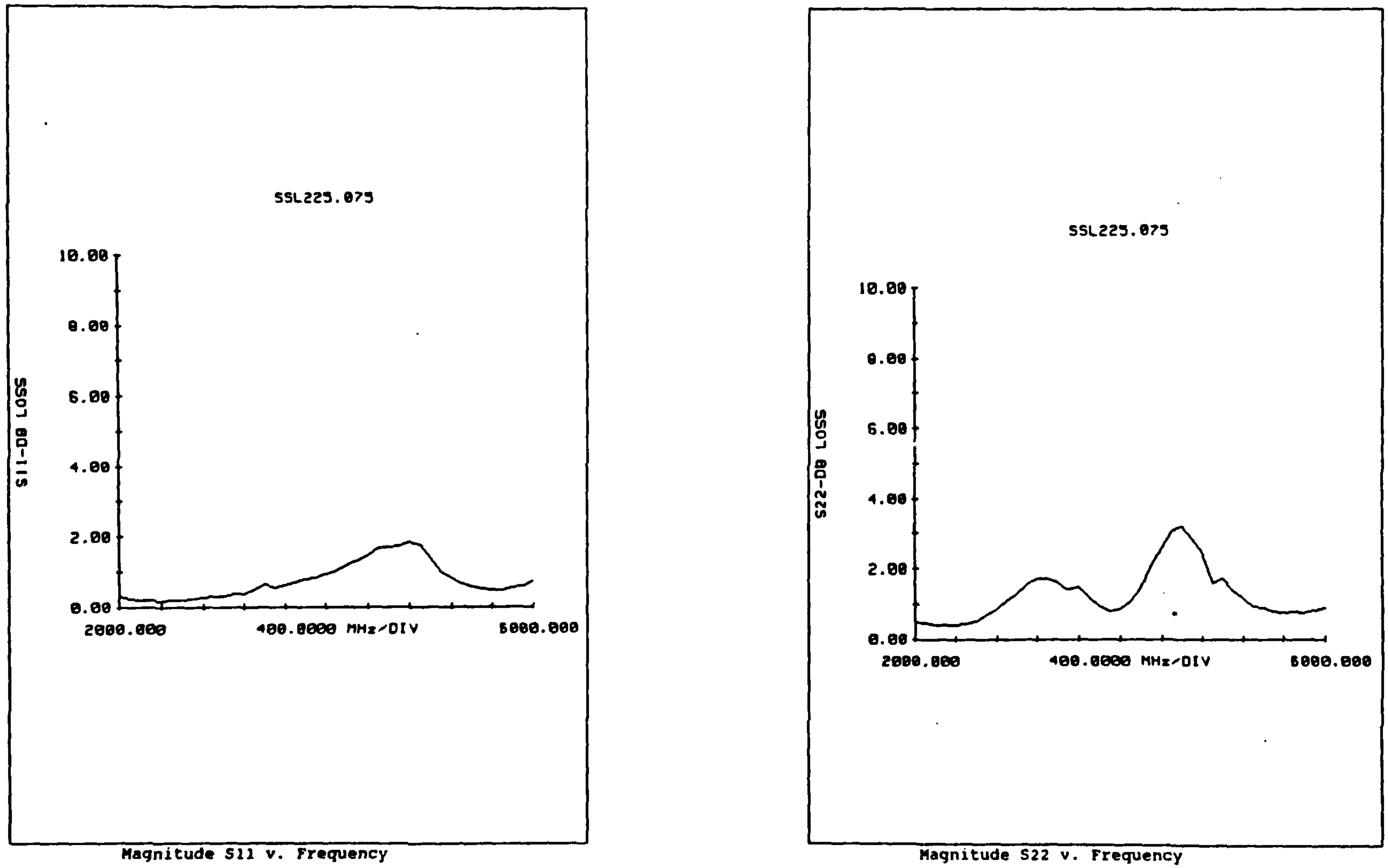


Figure 38. S11,S22 v. Frequency

w = .225" g= .075"

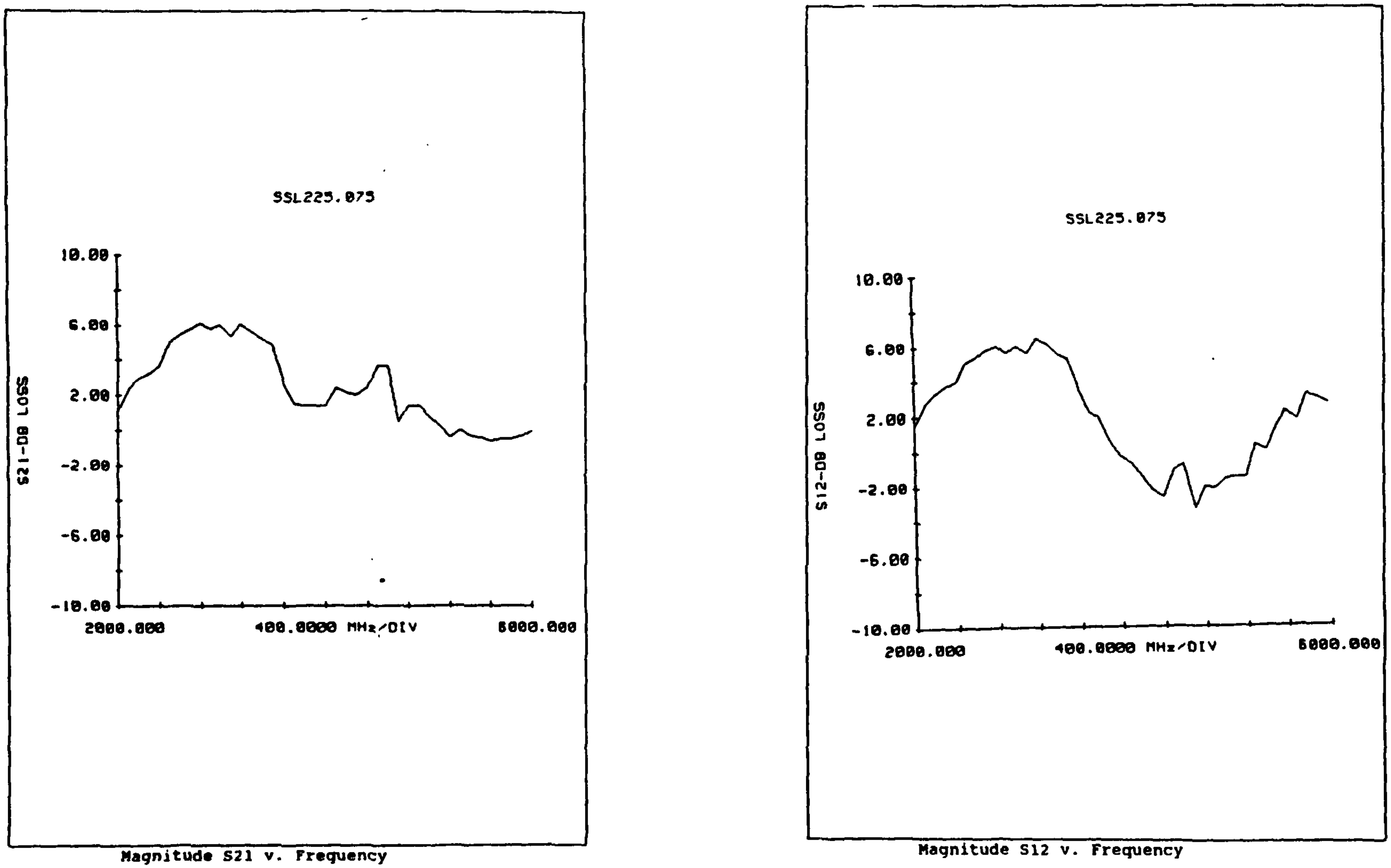


Figure 39. S21,S12 v. Frequency

w = .225" g= .075"

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APPENDIX C: TRL De-Embedding

A. FINDING THE LINE PARAMETERS

Both the attenuation and effective dielectric properties of the transmission line may be found from the measurements indicated in figures 1a and 1c. If there were no transition reflections, then it would be simple to get these values from the two S21 measurements. However, reflections from the transitions introduce errors which can be eliminated by the first part of a TRL program.

The scattering parameters derived from each of the four steps can easily be converted to transmission parameters:

Scattering Parameters	Transmission Parameters
$b_1 = s_{11}a_1 + s_{12}a_2$	$b_1 = r_{11}a_2 + r_{12}b_2$
$b_2 = s_{21}a_1 + s_{22}a_2$	$a_1 = r_{21}a_2 + r_{22}b_2$

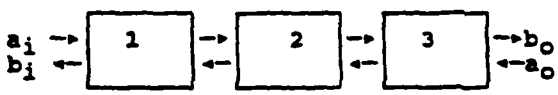
The relationship between the two parameters is

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix} = \frac{1}{S_{21}} \begin{bmatrix} -d_s & S_{11} \\ -S_{22} & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix} = \begin{bmatrix} & R & \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}$$

where $d_s = s_{11}s_{22} - s_{12}s_{21}$

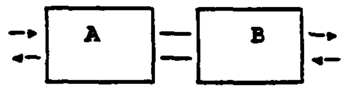
and the "R" matrix used here is sometimes called the "transmission" matrix.

The R matrix has a property similar to ABCD matrices; they may be multiplied in sequence (cascaded).



$$\begin{bmatrix} b_i \\ a_i \end{bmatrix} = \begin{bmatrix} R_1 \end{bmatrix} \cdot \begin{bmatrix} R_2 \end{bmatrix} \cdot \begin{bmatrix} R_3 \end{bmatrix} \cdot \begin{bmatrix} a_o \\ b_o \end{bmatrix}$$

1. Measure $\left[S_{AB} \right]$, the S parameters of the <u>through</u> connection.



Convert to $\left[R_{AB} \right]$, noting that $\left[R_{AB} \right] = \left[R_A \right] \cdot \left[R_B \right]$

2. Measure $\left[S_{ALB} \right]$, the S parameters of the through connection with the added length

Convert to $\left[R_{ALB} \right]$, where $\left[R_{ALB} \right] = \left[R_A \right] \cdot \left[R_L \right] \cdot \left[R_B \right]$

There is enough information from these two measurements to obtain the parameters of the transmission line used, i.e., the attenuation and phase velocity at each frequency. The added length must have the same characteristics as the line in which the DUT is to be embedded.

3. Find the matrix $\left[T \right] = \left[R_{ALB} \right] \cdot \left[R_{AB} \right]^{-1}$ (1)

Note that all the elements of the T matrix are known since the elements of R_{ALB} and R_{AB} were directly found from the S_{ALB} and S_{AB} measurements.

Using the cascade properties of the R matrix we have

$$\left[T \right] = \left[R_A \right] \cdot \left[R_L \right] \cdot \left[R_B \right] \cdot \left[R_{AB} \right]^{-1} = \left[R_A \right] \cdot \left[R_L \right] \cdot \left[R_B \right] \cdot \left[R_B \right]^{-1} \cdot \left[R_A \right]^{-1}$$

so that

$$\boxed{\left[T\right] = \left[R_A\right] \cdot \left[R_L\right] \cdot \left[R_A\right]^{-1}} \qquad (2)$$

The added line of length L is non-reflecting (same impedance as end of TRL transitions), so

$$\left[S_L\right] = \begin{bmatrix} 0 & \epsilon^{-\gamma L} \\ \epsilon^{-\gamma L} & 0 \end{bmatrix}$$

where $\gamma = \alpha + j\beta$

α= attenuation const
β= propagation const

Therefore

$$\left[R_L\right] = \begin{bmatrix} \epsilon^{-\gamma L} & 0 \\ 0 & \epsilon^{\gamma L} \end{bmatrix}$$

Using

$\left[T\right] \cdot \left[R_A\right] = \left[R_A\right] \cdot \left[R_L\right]$, we have

$$\begin{bmatrix} T_1 & T_2 \\ T_3 & T_4 \end{bmatrix} \cdot \begin{bmatrix} R_{A1} & R_{A2} \\ R_{A3} & R_{A4} \end{bmatrix} = \begin{bmatrix} R_{A1} & R_{A2} \\ R_{A3} & R_{A4} \end{bmatrix} \cdot \begin{bmatrix} \epsilon^{-\gamma L} & 0 \\ 0 & \epsilon^{\gamma L} \end{bmatrix}$$

Multiplying matrices we find:

(3) $T_1 \cdot R_{A1} + T_2 \cdot R_{A3} = R_{A1}\epsilon^{-\gamma L}$ (5) $T_1 \cdot R_{A2} + T_2 \cdot R_{A4} = R_{A2}\epsilon^{\gamma L}$

(4) $T_3 \cdot R_{A1} + T_4 \cdot R_{A3} = R_{A3}\epsilon^{-\gamma L}$ (6) $T_3 \cdot R_{A2} + T_4 \cdot R_{A4} = R_{A4}\epsilon^{\gamma L}$

From 3,4 we have

$$\frac{R_{A1}}{R_{A3}} = \frac{T_2}{\epsilon^{-\gamma L} - T_1} = \frac{\epsilon^{-\gamma L} - T_4}{T_3} \qquad (7)$$

so that $$\epsilon^{-2\gamma L} - \epsilon^{-\gamma L}(T_1 + T_4) + (T_1T_4 - T_2T_3) = 0 \tag{8}$$

From 5,6 we have $$\frac{R_{A2}}{R_{A4}} = \frac{T_2}{\epsilon^{\gamma L} - T_1} = \frac{\epsilon^{\gamma L} - T_4}{T_3} \tag{9}$$

so that $$\epsilon^{2\gamma L} - \epsilon^{\gamma L}(T_1 + T_4) + (T_1T_4 - T_2T_3) = 0 \tag{10}$$

The solutions for $\epsilon^{-\gamma L}$ and $\epsilon^{\gamma L}$ are the two solutions to the complex equation

$$G^2 - G(T_1+T_4) + (T_1T_4 - T_2T_3) = 0$$

we find

$$G = B\cdot\left[1 \pm D^{1/2}\right] \quad \text{with solutions } |G_1|\cdot\epsilon^{jtg1},\ |G_2|\cdot\epsilon^{jtg2} \tag{11}$$

where $$B = \frac{T_1 + T_4}{2} \qquad C = T_1T_4 - T_2T_3 \qquad D = 1 - \frac{C}{B^2}$$

The solution for $\epsilon^{-\gamma L} = \epsilon^{-\alpha L}\cdot\epsilon^{-j\beta L}$ will be

$|G_1|\cdot\epsilon^{jtg1}$ if tg1 is negative

$|G_2|\cdot\epsilon^{jtg2}$ if tg2 is negative

The attenuation (dB) in the distance L is $20*\log_{10}(G_{1,2})$ so

$$\boxed{\text{dB/inch} = \frac{20*\log_{10}(G_{1,2})}{L(\text{in.})}} \tag{12}$$

where $G_{1,2}$ is the correct solution as found above

Also, since $\beta L = t_g = 2\pi \cdot L/\text{wavelength} = \dfrac{2\pi \cdot L \cdot f \cdot \sqrt{e_{eff}}}{c}$

$$\boxed{e_{eff} = \{\ 30 \cdot t_g/[2.54 \cdot 2\pi \cdot L(in) \cdot f(gHz]\ \}^2} \qquad (13)$$

We have found the transmission line parameters dB/inch and e_{eff} from measuring the S parameters of the two fixtures with different lengths.

For low loss media such as suspended substrate, the added length L should be large enough so that the transmission loss of the larger line will be evident. The added line may need to be a centimeter or longer. Since measurements of the phase of s11 and s22 are ambiguous by multiples of 2π radians if L is larger than 1/2 wavelength, one can resolve the ambiguity in t_g as follows:

a. Estimate e_{eff} and find an approximate t_g.

b. Use this value to calculate e_{eff}^{o}, e_{eff}^{+}, and e_{eff}^{-} for the approximated values of t_g, $t_g+2\pi$, and $t_g-2\pi$ respectively.

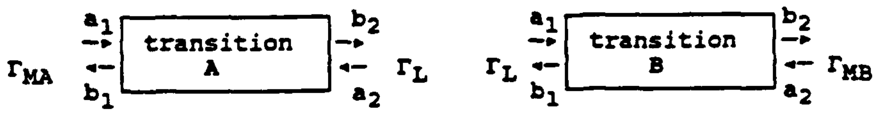
c. Choose which of the three values comes closest to the estimated e_{eff}.

Generally, for L one or two wavelengths long, the other two values will be very far off.

B. FINDING THE TRANSITION PARAMETERS

We now turn to the rest of the de-embedding process.

Using identical loads, do the Reflect measurements, finding Γ_{MA} and Γ_{MB}. It is not necessary to know the load value, only that it is the same for the two reflect measurements. Taking identical lengths off the ends of the TRL transitions provides the simplest of loads.



$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix}_A = \begin{bmatrix} R_{A1} & R_{A2} \\ R_{A3} & R_{A4} \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_A = R_{A4} \cdot \begin{bmatrix} A_1 & A_2 \\ A_3 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_A$$

$$(b_1/a_1)_A = \Gamma_{MA} = \frac{A_1(a_2/b_2) + A_2}{A_3(a_2/b_2) + 1} = \frac{A_1\Gamma_L + A_2}{A_3\Gamma_L + 1} \qquad (14)$$

define $\boxed{X1 = R_{A1}/R_{A3} = A_1/A_3}$ and (15)

$$\boxed{X2 = R_{A2}/R_{A4} = A_2} \qquad (16)$$

where these values were completely determined in (7) and (9).

we find from (14)

$$A_1 = \frac{\Gamma_{MA} - X2}{\Gamma_L(1-\Gamma_{MA}/X1)} \qquad (17)$$

where all values are now known except Γ_L

Similarly,

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix}_B = \begin{bmatrix} R_{B1}/R_{B4} & R_{B2}/R_{B4} \\ R_{B3}/R_{B4} & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_B = R_{B4} \cdot \begin{bmatrix} B_1 & B_2 \\ B_3 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_B$$

$$(b_1/a_1)_B = \frac{1}{\Gamma_L} = \frac{B_1 + B_2(b_2/a_2)_B}{B_3 + (b_2/a_2)_B} = \frac{B_1 + B_2 \cdot \Gamma_{MB}}{B_3 + \Gamma_{MB}} \qquad (18)$$

We now find the B values, hence Γ_L, and finally, from (17), A_1.

From measurements:

$$\begin{bmatrix} R_{AB} \end{bmatrix} = \begin{bmatrix} R_{AB1} & R_{AB2} \\ R_{AB3} & R_{AB4} \end{bmatrix} = R_{AB4} \cdot \begin{bmatrix} AB1 & AB2 \\ AB3 & 1 \end{bmatrix} \quad \text{known, and since}$$

$$\begin{bmatrix} R_B \end{bmatrix} = \begin{bmatrix} R_A \end{bmatrix}^{-1} \cdot \begin{bmatrix} R_{AB} \end{bmatrix}$$

$$\begin{bmatrix} R_B \end{bmatrix} = R_{B4} \cdot \begin{bmatrix} B_1 & B_2 \\ B_3 & 1 \end{bmatrix} = \frac{R_{AB4}}{R_{A4}(A_1 - A_2 \cdot A_3)} \begin{bmatrix} 1 & -A_2 \\ -A_3 & A_1 \end{bmatrix} \cdot \begin{bmatrix} AB_1 & AB_2 \\ AB_3 & 1 \end{bmatrix}$$

solving for RB_4, we have

$$\begin{bmatrix} B_1 & B_2 \\ B_3 & 1 \end{bmatrix} = \frac{1}{(A_1 - A3 \cdot AB_2)} \begin{bmatrix} 1 & -A_2 \\ -A_3 & A_1 \end{bmatrix} \cdot \begin{bmatrix} AB_1 & AB_2 \\ AB_3 & 1 \end{bmatrix}$$

$$\boxed{B_1 = \frac{AB_1 - X2 \cdot AB_3}{A_1 \cdot (1 - AB_2/X1)}} \tag{19}$$

$$\boxed{B_2 = \frac{AB_2 - X_2}{A_1(1 - AB_2/X1)}} \tag{20}$$

$$\boxed{B_3 = \frac{AB_3 - AB_1/X1}{1 - AB_2/X1}} \tag{21}$$

Eliminating the unknown Γ_L from (17) and (18) gives

$$\frac{A_1}{B_1} = \frac{(\Gamma_{MA} - X2) \cdot (1 + [B_2/B_1] \cdot \Gamma_{MB})}{(1 - \Gamma_{MA}/X1) \cdot (B_3 + \Gamma_{MB})}, \quad \text{all known} \tag{22}$$

Multiplying (22) by (19) yields two solutions for A_1

$$A_1 = \pm \left[\frac{(\Gamma_{MA} - X2)\cdot(1 + [B_2/B_1]\cdot\Gamma_{MB})\cdot(AB_1 - x2\cdot AB_3)}{(\Gamma_{MB} + B_3)\cdot(1 - \Gamma_{MA}/X1)\cdot(1 - AB_2/X1)} \right]^{1/2} \qquad (23)$$

$$\begin{aligned} A_1 &= a_1\cdot\epsilon^{jTax1} && \text{for } +\surd \\ &= a_1\cdot\epsilon^{jTax1+\pi} && \text{for } -\surd \end{aligned}$$

where a_1 is a positive real number.

To find which solution is to be used, find the approximate value of A_1. If an ideal open circuit were used for the reflect measurement, $\Gamma_L = 1$. Substituting in (17) we find the approximate value of A_1.

$$A_1 \approx \frac{\Gamma_{MA} - X2}{1 - \Gamma_{MA}/X1} = A_{1x} = |a_{1x}|\cdot\epsilon^{jTax}, \text{ all known} \qquad (24)$$

Now that we've calculated the phase angle that A_1 would have with an ideal open circuit, we can compare that phase angle with the angles derived from the non-ideal opens. The winner is the angle closest to T_{ax}. This is shown diagrammatically in Figure A1.

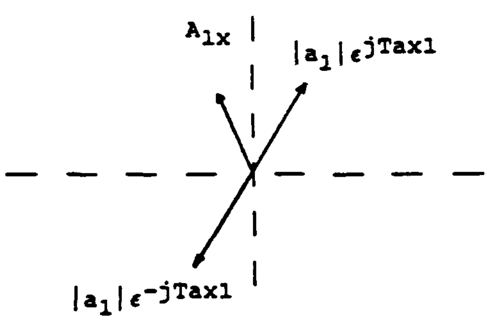


Figure A1. Determining the correct phase of A_1

All values of the A matrix are now known.

C. DE-EMBEDDING THE DEVICE

The device is inserted at the reference position, that is, the junction of TRL transitions 1 and 2 (Figure A2). This position need not be at the center of the line.

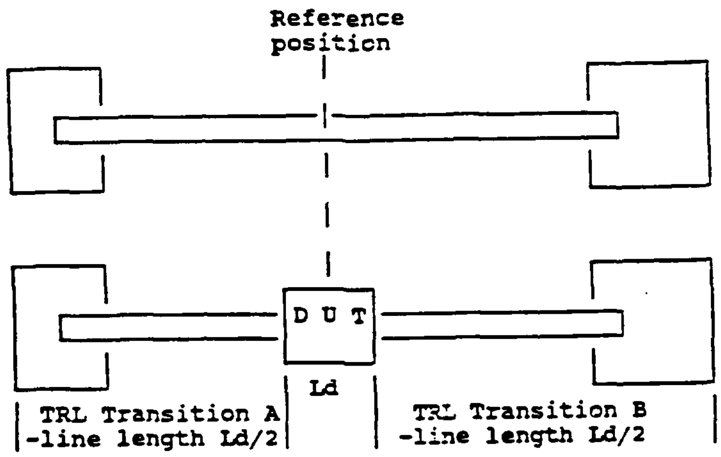


Figure A2. Inserting the device at the reference position

$\left[R_{ADB} \right]$ can be written to include the negative line lengths -Ld/2 taken by the DUT from the TRL transition line lengths.

The R matrix for negative line length -Ld/2 is

$$\left[R_N \right] = \begin{bmatrix} \epsilon^{\gamma Ld/2} & 0 \\ 0 & \epsilon^{-\gamma Ld/2} \end{bmatrix} \qquad (25)$$

so

$$\left[R_{ADB} \right] = \left[R_A \right] \cdot \left[R_N \right] \cdot \left[R_D \right] \cdot \left[R_N \right] \cdot \left[R_B \right]$$

$$= R_{A4} \cdot R_{B4} \cdot \left[AR_N \right] \cdot \left[R_D \right] \cdot \left[R_N B \right] \qquad (26)$$

$$\left[R_D \right] = \frac{1}{R_{A4} \cdot R_{B4}} \left[AR_N \right]^{-1} \cdot \left[R_{ADB} \right] \cdot \left[R_N B \right]^{-1} \qquad (27)$$

The values R_{A4} and R_{B4} have not yet been determined. We can write

$$\left[R_{AB} \right] = R_{A4} \cdot R_{B4} \left[A \right] \cdot \left[B \right] \quad \text{which yields}$$

$$R_{AB4} = R_{A4} \cdot R_{B4} \cdot (1 + A_3 \cdot B_2). \tag{28}$$

Substituting (28) into (27) gives the result

$$\boxed{\left[R_D \right] = \frac{(1 + A_3 \cdot B_2)}{R_{AB4}} \cdot \left[AR_N \right]^{-1} \cdot \left[R_{ADB} \right] \cdot \left[R_N B \right]^{-1}} \tag{29}$$

Examination of this equation shows that all values to the right of the = sign have been determined; therefore the device transmission parameters can be calculated.

Finally, the 4-port device R parameters can be converted to the device S parameters by the standard transformation methods.

$$\boxed{\left[S_D \right] = \frac{1}{R_{22}} \begin{bmatrix} R_{12} & d_r \\ 1 & -R_{21} \end{bmatrix} , \quad d_r = R_{11} \cdot R_{22} - R_{12} \cdot R_{21}} \tag{30}$$

APPENDIX D. DE-Embedded Data

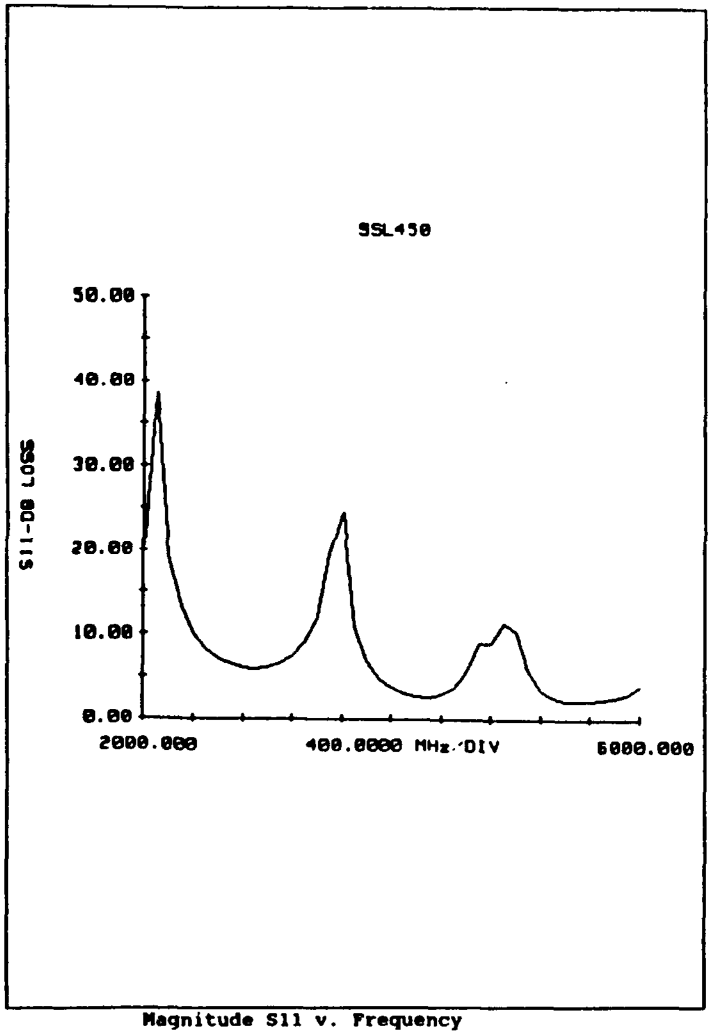
The following is the de-embedded measured S-parameters using a program written by [Ref. 7] using the methodology discussed by Appendix C. which was written by [Ref. 7]. The data includes the four required device measurements which were essential in the de-embedding process.

Table 16. MEASURED THROUGH S-PARAMETERS OF SHIELDED SSL
W= .450"

SSL450

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-OUT S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	19.27	-91.2	.18	176.0	.0008	.18	176.3	18.40	-82.5
2100.0000	38.52	-63.0	.15	147.3	.0008	.15	147.7	33.44	-94.5
2200.0000	19.23	20.7	.15	119.9	.0008	.13	120.3	20.38	34.5
2300.0000	13.26	-6.7	.26	90.3	.0008	.24	90.7	13.56	8.3
2400.0000	10.05	-34.4	.46	60.9	.0008	.51	61.5	9.93	-17.9
2500.0000	8.21	-63.0	.72	33.5	.0008	.76	34.4	7.80	-44.5
2600.0000	7.05	-91.3	.93	5.5	.0007	.94	6.5	6.42	-70.2
2700.0000	6.47	-118.3	1.27	-20.2	.0007	1.36	-18.8	5.65	-94.3
2800.0000	6.07	-146.5	1.46	-44.9	.0007	1.48	-43.5	5.13	-120.6
2900.0000	5.91	-173.2	1.47	-70.6	.0007	1.48	-69.3	4.96	-144.8
3000.0000	6.06	161.4	1.30	-94.4	.0007	1.24	-93.9	5.03	-168.7
3100.0000	6.46	133.9	1.04	-118.2	.0007	.95	-118.1	5.55	165.9
3200.0000	7.36	[illegible]	[illegible]	-144.[illegible]	.0007	[illegible]	-144.[illegible]	6.57	141.3
3300.0000	8.99	78.3	.56	-171.0	.0008	.40	-170.9	8.61	113.1
3400.0000	12.14	58.1	.40	156.9	.0009	.34	159.5	12.34	86.1
3500.0000	19.49	29.7	.33	126.4	.0009	.25	127.1	21.38	61.4
3600.0000	24.49	162.4	.20	94.5	.0008	.18	94.9	19.08	-143.6
3700.0000	10.92	132.8	.55	64.0	.0009	.45	64.0	9.67	173.8
3800.0000	6.88	100.3	1.08	33.4	.0008	.98	33.3	6.40	142.7
3900.0000	4.71	71.6	1.77	5.8	.0007	1.68	6.1	4.59	114.7
4000.0000	3.66	45.6	2.35	-20.1	.0006	2.27	-20.5	3.67	89.3
4100.0000	2.97	21.0	2.85	-43.1	.0007	2.56	-43.4	3.13	66.0
4200.0000	2.67	-2.6	3.42	-66.5	.0007	3.17	-66.3	2.94	42.9
4300.0000	2.59	-25.6	3.68	-91.1	.0007	3.46	-88.6	2.96	20.1
4400.0000	2.86	-48.0	3.30	-117.4	.0007	3.31	-115.0	3.31	-.7
4500.0000	3.65	-71.3	2.16	-142 7	.0008	2.52	-141.5	3.74	-23.9
4600.0000	5.33	-93.7	1.26	-170.7	.0009	1.51	-169.8	5.14	-49.4
4700.0000	8.08	-106.5	.97	157.7	.0008	.90	157.5	9.18	-70.1
4800.0000	9.00	-102.3	2.32	128.6	.0006	2.20	129.2	11.34	-59.6
4900.0000	11.34	-113.7	1.68	107.4	.0010	1.63	108.9	14.34	-79.7
5000.0000	10.38	-87.0	1.10	70.6	.0010	1.09	72.0	14.50	-6.5
5100.0000	5.78	-97.6	1.62	33.2	.0009	1.90	34.4	6.23	-26.1
5200.0000	3.47	-120.2	2.90	.2	.0008	3.26	3.3	3.27	-56.3
5300.0000	2.54	-144.1	4.24	-26.8	.0007	4.56	-25.0	2.02	-83.2
5400.0000	2.22	-165.3	5.02	-51.3	.0004	5.41	-52.4	1.56	-106.7
5500.0000	2.10	174.8	6.02	-65.5	.0006	6.08	-66.6	1.34	-130.1
5600.0000	2.12	156.3	6.41	-85.4	.0006	5.78	-86.4	1.37	-152.4
5700.0000	2.35	138.7	6.07	-106.6	.0006	11.16	171.2	1.51	-173.0
5800.0000	2.47	119.4	6.54	-127.9	.0007	11.97	50.0	1.91	162.3
5900.0000	2.91	100.3	5.39	-154.2	.0007	12.57	-72.1	2.58	136.3
6000.0000	3.93	78.5	3.72	-179.2		14.06	161.7	3.91	106.0

Through Measurement S-parameters W=.450"



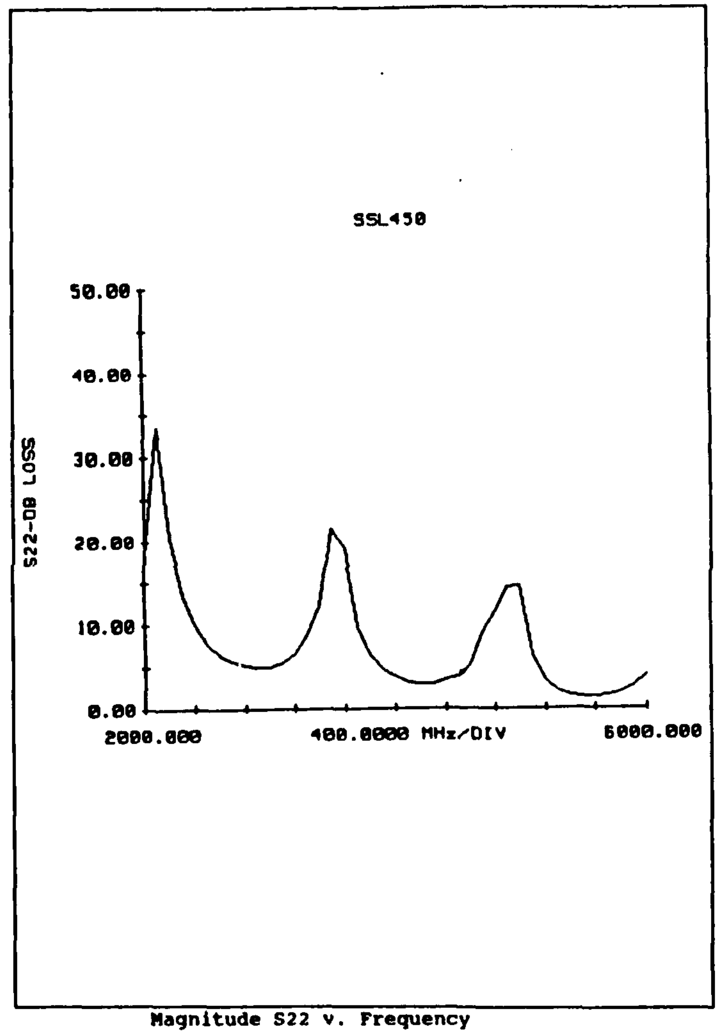
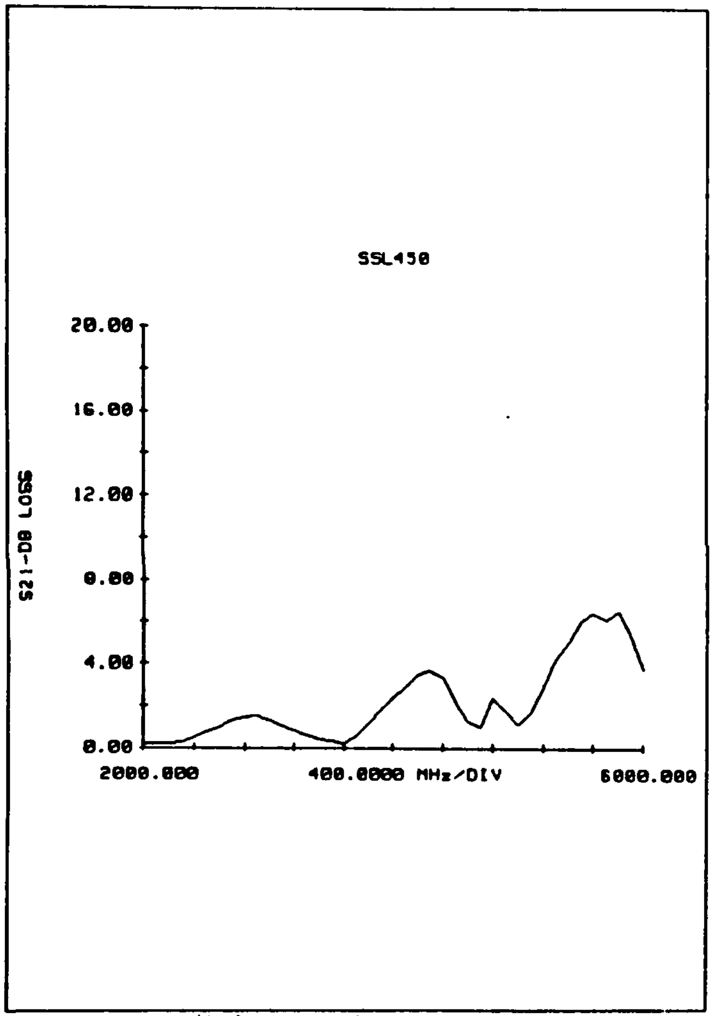
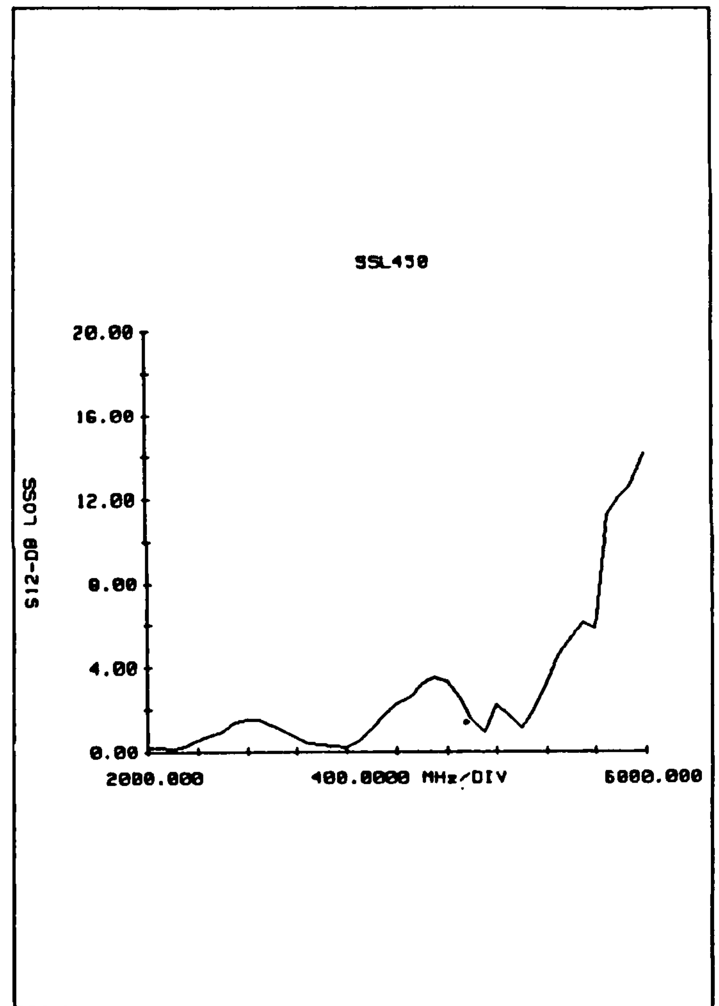


Figure 40. S11,S22 v. Frequency

w = .450"



Magnitude S21 v. Frequency



Magnitude S12 v. Frequency

Figure 41. S21,S12 v. Frequency

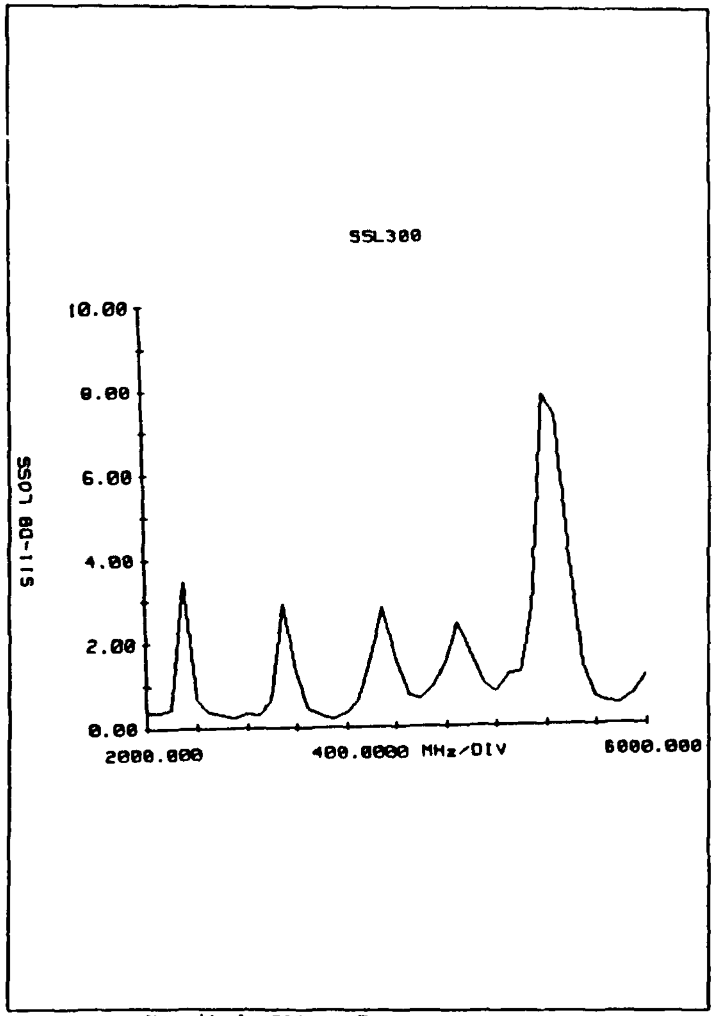
w = .450"

Table 17. MEASURED THROUGH S-PARAMETERS OF SHIELDED SSL
W= .300"

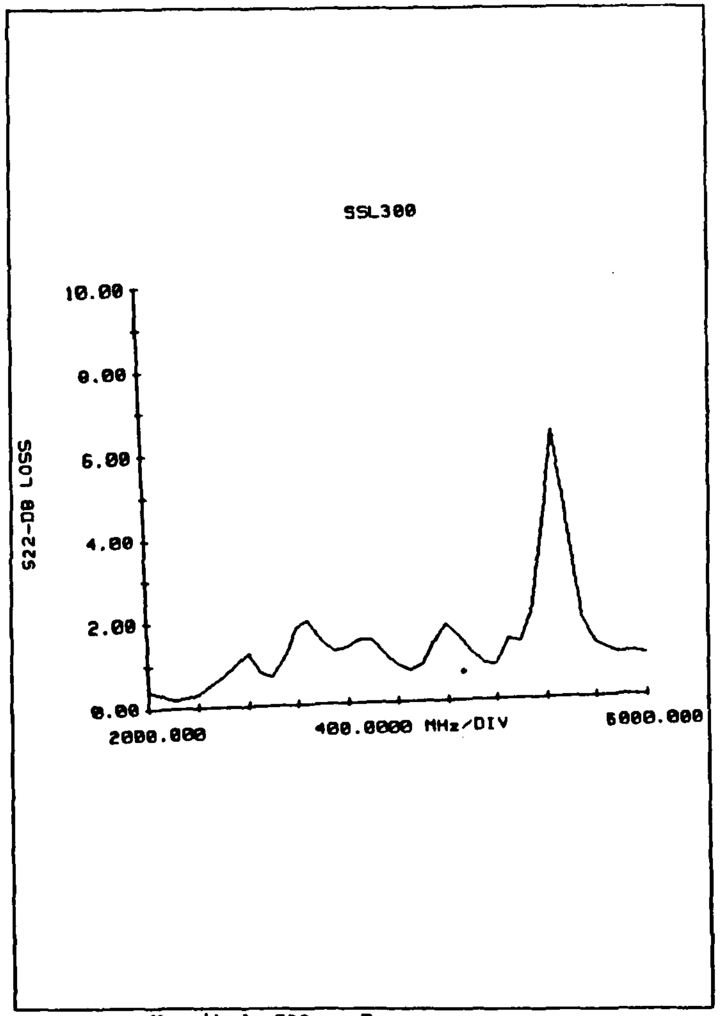
SSL300

FREQUENCY	RETURN LOSS-IN		LOSS-FORWARD			LOSS-REVERSE		RETURN LOSS-OUT	
	S11		S21		DELAY	S12		S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	.38	151.7	11.50	-95.8	.0003	14.05	-106.6	.40	127.7
2100.0000	.35	134.9	9.20	-106.2	.0004	14.12	-129.6	.30	85.2
2200.0000	.44	110.3	4.41	-119.4	.0018	13.90	-148.5	.20	46.4
2300.0000	3.46	-19.3	-6.60	174.5	.0024	13.17	-168.2	.22	8.1
2400.0000	.67	146.6	2.30	87.6	.0005	12.25	172.6	.30	-30.4
2500.0000	.37	117.5	8.24	69.1	.0003	10.92	148.8	.51	-70.3
2600.0000	.29	99.4	9.69	58.1	.0001	8.98	126.4	.70	-116.0
2700.0000	.24	81.4	9.70	52.9	.0003	7.45	109.2	.97	-168.4
2800.0000	.32	63.5	9.45	43.0	.0004	5.94	77.3	1.24	132.5
2900.0000	.28	40.1	7.15	28.1	.0006	3.80	42.0	.77	67.5
3000.0000	.61	-.5	2.56	7.6	.0017	2.35	9.1	.67	-1.3
3100.0000	[illegible]	125.0	-2.21	[illegible]	.0017	1.70	[illegible]	[illegible]	[illegible]
3200.0000	1.30	108.6	2.05	-113.2	.0007	1.05	-57.7	1.78	-133.7
3300.0000	.45	56.2	5.91	-140.1	.0003	-.20	-95.2	1.96	155.9
3400.0000	.26	29.1	7.23	-151.9	.0003	-1.50	-128.4	1.48	74.1
3500.0000	.19	5.7	7.85	-164.0	.0004	-1.04	-173.2	1.24	-12.1
3600.0000	.34	-18.7	7.10	-179.7	.0005	.25	146.5	1.29	-87.7
3700.0000	.63	-50.7	5.45	163.2	.0007	2.05	119.1	1.48	-151.5
3800.0000	1.53	-99.7	2.90	138.5	.0011	3.65	95.4	1.46	156.6
3900.0000	2.81	173.5	.39	97.3	.0013	4.08	69.4	1.13	108.5
4000.0000	1.66	72.3	.35	51.1	.0009	3.76	45.2	.87	61.9
4100.0000	.77	12.2	2.25	20.3	.0006	3.55	21.3	.72	14.5
4200.0000	.63	-28.7	3.20	-1.8	.0006	3.10	-6.1	.85	-38.2
4300.0000	.92	-67.1	2.70	-22.7	.0006	2.35	-38.0	1.39	-99.0
4400.0000	1.49	-115.9	.85	-45.2	.0012	1.65	-68.7	1.78	-169.5
4500.0000	2.43	161.2	-.40	-86.8	.0013	2.75	-104.7	1.53	116.9
4600.0000	1.77	59.8	.45	-134.0	.0043	3.86	-137.3	1.12	53.3
4700.0000	1.00	-4.2	-.51	71.3	.0079	1.41	72.6	.86	-.0
4800.0000	.78	-44.7	1.65	147.5	.0079	2.55	144.6	.82	-46.9
4900.0000	1.19	-73.9	2.31	-137.4	.0080	3.15	-148.2	1.41	-87.5
5000.0000	1.23	-112.2	1.08	-66.7	.0081	2.82	-83.1	1.33	-138.8
5100.0000	2.74	-164.1	-1.35	2.1	.0086	1.45	-14.5	2.00	162.0
5200.0000	7.81	100.2	-2.70	52.9	.0082	1.05	44.3	4.12	98.1
5300.0000	7.31	-3.5	-.75	119.1	.0085	3.85	115.2	6.31	24.5
5400.0000	3.89	-45.9	-1.28	171.7	.0083	3.34	-173.1	3.96	-27.5
5500.0000	1.36	-78.6	6.20	-125.9	.0073	5.40	-110.4	1.91	-83.0
5600.0000	.65	-109.3	7.29	-28.0	.0078	7.14	-35.6	1.26	-129.8
5700.0000	.49	-134.4	6.10	50.4	.0076	7.20	35.0	1.10	-168.3
5800.0000	.48	-158.4	5.00	130.3	.0078	6.75	119.1	1.01	157.4
5900.0000	.66	175.8	2.41	-141.2	.0078	5.76	-161.8	1.02	123.0
6000.0000	1.12	138.9	-.26	-63.4		5.50	-82.2	.94	86.2

Through Measurement S-parameters w=.300"



Magnitude S11 v. Frequency



Magnitude S22 v. Frequency

Figure 42. S11,S22 v. Frequency

W = .300"

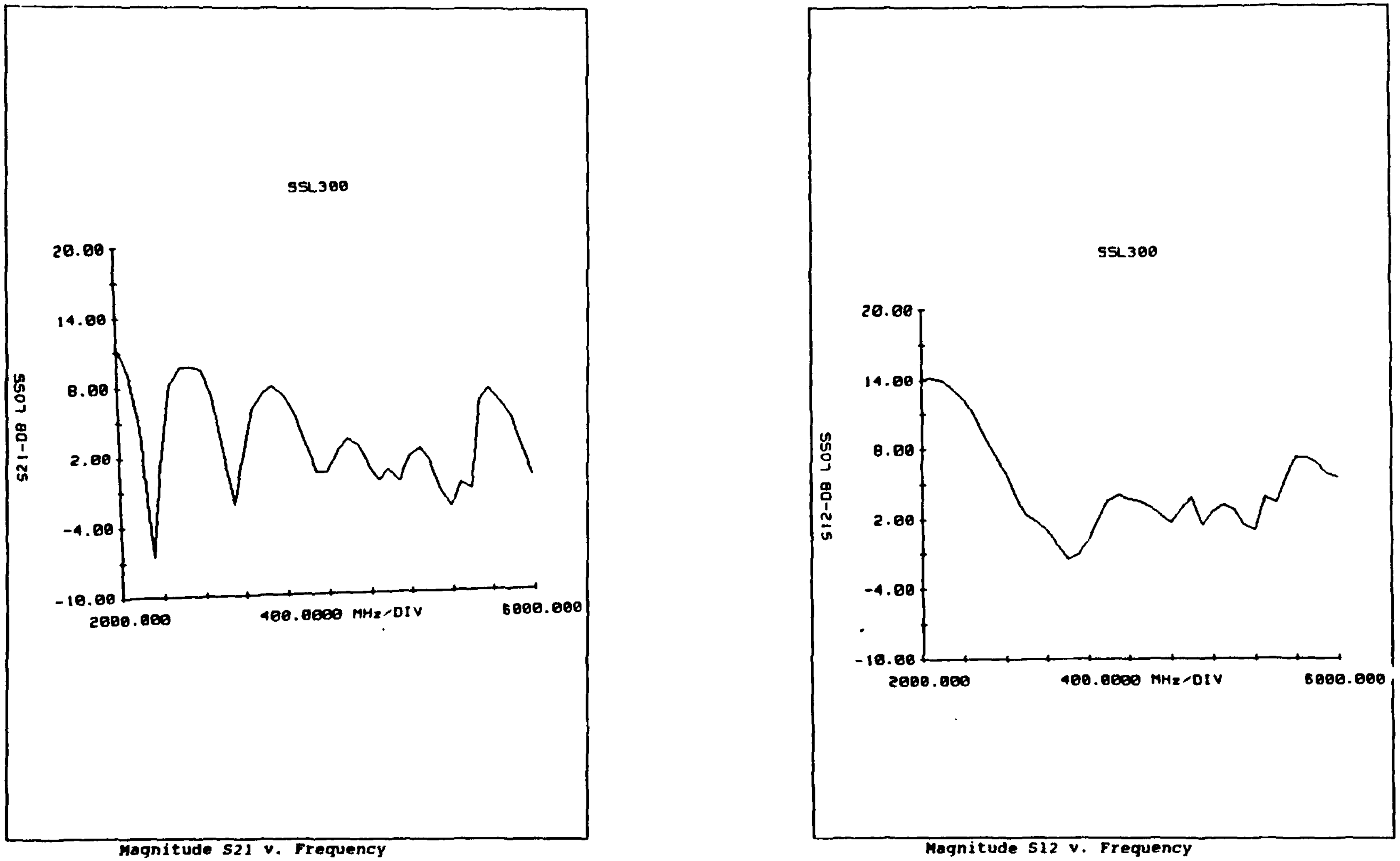


Figure 43. S21,S12 v. Frequency

w = .300"

Table 18. MEASURED THROUGH S-PARAMETERS OF SHIELDED SSL W= .225"

SSL225

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-OUT S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	3.61	80.3	3.64	175.6	.0012	4.57	176.2	3.49	71.6
2100.0000	1.14	22.1	13.91	133.1	.0091	14.87	135.0	.95	20.6
2200.0000	24.20	172.4	.14	164.3	.0013	.92	164.3	19.40	-16.1
2300.0000	9.98	47.9	.40	117.3	.0010	1.08	117.4	10.14	19.8
2400.0000	10.77	18.1	.58	82.1	.0012	1.31	82.4	11.25	-9.1
2500.0000	19.99	22.7	.86	40.6	.0016	1.00	40.4	25.73	-82.2
2600.0000	2.65	24.6	9.76	-17.7	.0087	10.53	-15.6	2.80	27.0
2700.0000	3.30	-36.1	5.33	30.2	.0011	6.16	29.8	3.46	-41.8
2800.0000	6.92	-84.5	1.77	-7.9	.0007	2.55	-8.4	7.17	-91.8
2900.0000	8.26	-128.9	.76	-34.8	.0010	1.69	-35.0	8.62	-136.4
3000.0000	12.09	-159.5	.53	-71.8	.0010	1.51	-72.3	12.84	-164.0
3100.0000	15.77	107.4	.61	-107.2	.0013	1.53	-106.7	16.24	104.0
3200.0000	11.92	93.1	.67	-1?2.5	.0093	1.35	-151.9	12.31	97.1
3300.0000	1.95	-10.2	9.99	-126.4	.0010	10.63	-126.3	1.95	-10.2
3400.0000	3.44	-73.4	3.15	-163.6	.0010	4.17	-163.7	3.43	-76.1
3500.0000	5.52	-113.6	1.85	156.8	.0009	2.74	159.4	5.50	-118.9
3600.0000	6.73	-134.2	1.63	124.9	.0008	2.49	125.3	6.65	-142.2
3700.0000	4.87	-166.8	2.63	94.7	.0004	3.61	94.9	4.60	-176.7
3800.0000	23.97	156.0	-4.16	80.1	.0065	5.76	81.7	17.33	113.9
3900.0000	-9.70	91.1	-12.70	-153.8	.0029	-3.37	-19.9	-9.46	84.1
4000.0000	2.22	41.7	4.22	101.3	.0038	11.54	-10.7	1.58	37.5
4100.0000	4.00	36.1	5.96	-35.1	.0019	9.82	-13.6	2.66	30.6
4200.0000	.82	-23.9	3.13	-102.1	.0078	6.62	47.7	.06	-14.7
4300.0000	-2.46	105.0	-6.18	-22.8	.0025	-2.65	-98.0	.32	120.7
4400.0000	9.28	-66.9	-3.46	-112.2	.0074	1.38	-59.7	4.18	-68.7
4500.0000	-3.88	56.7	-3.74	-20.1	.0022	1.45	147.2	-4.08	63.6
4600.0000	2.64	32.7	5.36	-99.8	.0037	11.34	-170.5	3.09	35.0
4700.0000	1.23	21.7	12.94	128.5	.0014	17.67	172.1	1.26	21.6
4800.0000	-.09	-11.5	4.35	78.2	.0073	6.10	-113.2	-.24	-10.1
4900.0000	-1.85	131.6	-6.38	173.8	.0029	-3.57	105.3	.29	142.4
5000.0000	6.92	-67.5	-1.79	68.3	.0077	-.29	141.5	1.56	-57.0
5100.0000	-1.56	52.8	-.16	149.4	.0021	3.22	-9.7	-.79	70.8
5200.0000	2.20	15.5	6.59	74.2	.0036	11.74	43.6	4.36	10.3
5300.0000	-2.03	6.2	4.96	-54.3	.0023	12.41	39.1	4.00	-2.4
5400.0000	-2.68	-24.2	-3.31	-138.0	.0061	5.75	56.3	-3.00	-45.1
5500.0000	4.69	-158.7	-7.07	2.0	.0026	.99	-44.6	-.63	162.8
5600.0000	4.60	-68.3	-3.42	-93.2	.0048	5.31	-28.5	9.82	-120.4
5700.0000	-7.91	-170.5	-11.24	95.7	.0042	-4.02	-101.8	-8.15	164.8
5600.0000	5.12	117.6	-.28	-55.1	.0044	3.92	-124.6	2.74	96.8
5900.0000	-1.87	147.7	-4.13	147.8	.0042	-.92	-150.2	-1.36	136.7
6000.0000	.65	22.2	19.27	-3.1		21.32	-161.1	.70	23.3

Through Measurement S-parameters w=.225

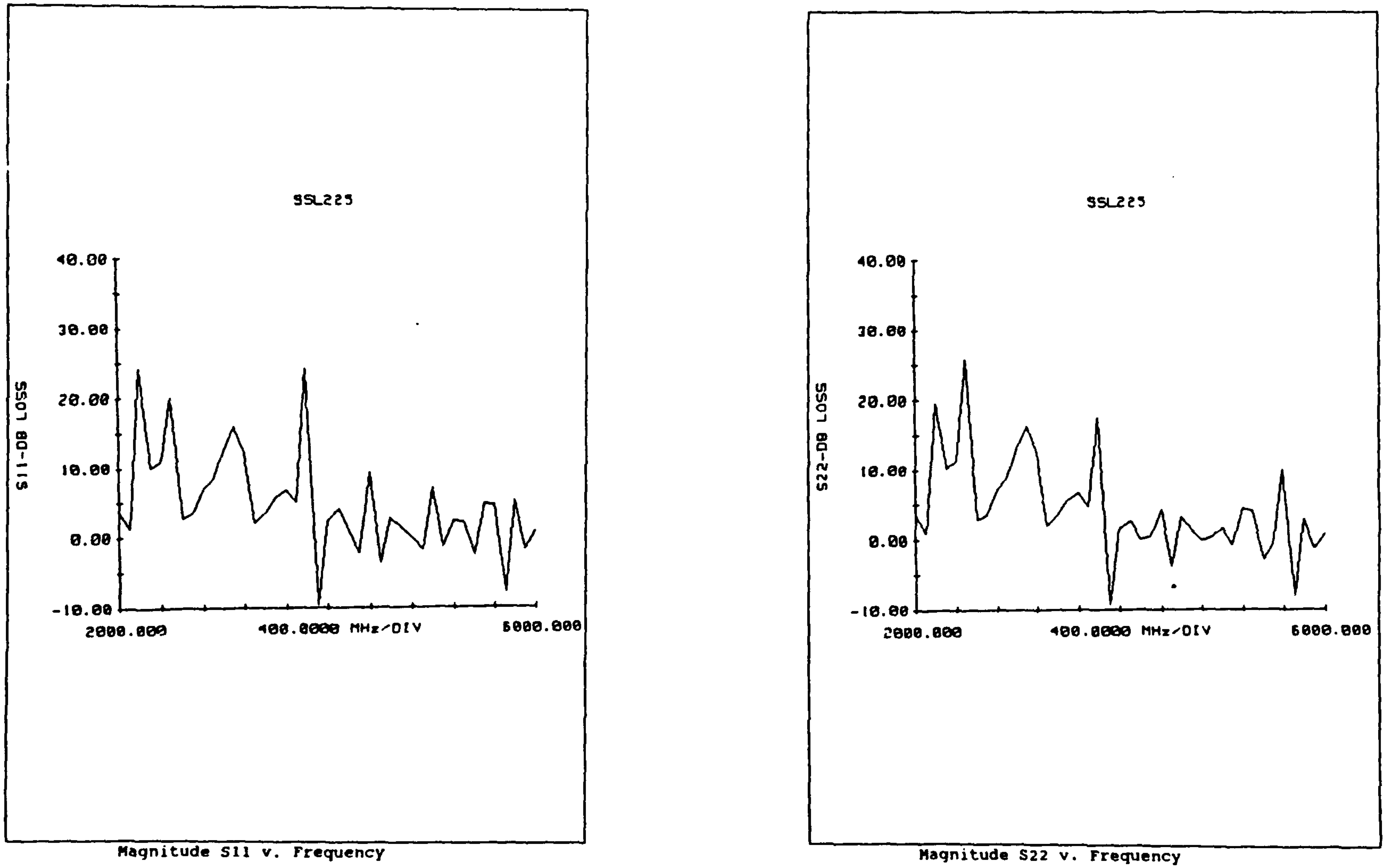
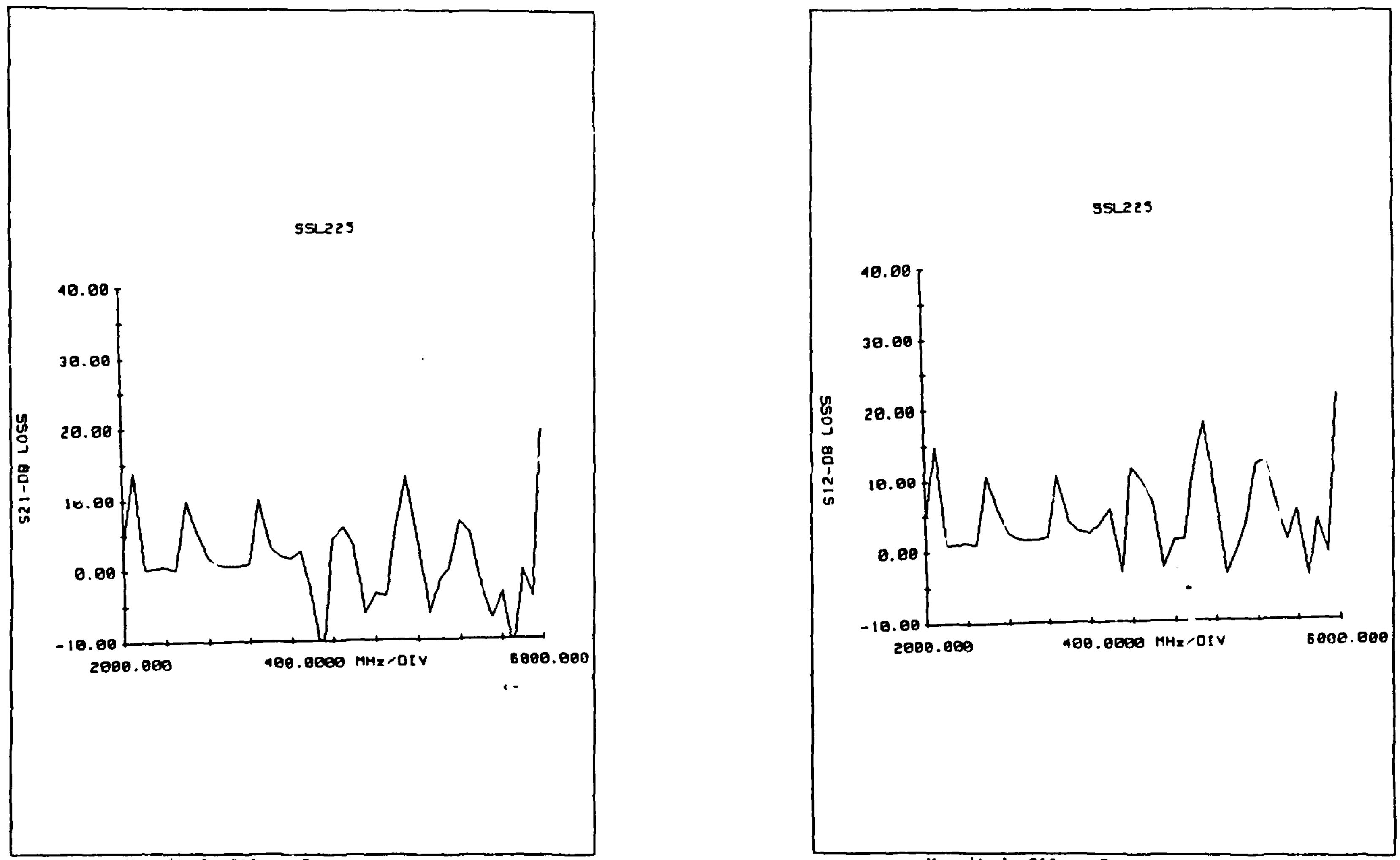


Figure 44. S11,S22 v. Frequency

W = .225"



Magnitude S21 v. Frequency

Magnitude S12 v. Frequency

Figure 45. S21,S12 v. Frequency

W = .225"

Table 19. MEASURED REFLECT S-PARAMETERS OF TRL TRANSITION A W= .450"

TRL TRANSITION A REFLECT W=.~~225~~ .450

FREQUENCY MHz	RETURN LOSS-IN S11 DB	ANG
2000.0000	.51	-167.1
2100.0000	.44	163.6
2200.0000	.36	133.9
2300.0000	.31	104.2
2400.0000	.27	74.8
2500.0000	.32	43.9
2600.0000	.41	13.8
2700.0000	.61	-15.5
2800.0000	.70	-44.7
2900.0000	.74	-72.1
3000.0000	.82	-101.1
3100.0000	.89	-129.2
3200.0000	.91	-156.3
3300.0000	.93	177.1
3400.0000	.86	152.5
3500.0000	.76	126.5
3600.0000	1.00	101.4
3700.0000	.85	80.4
3800.0000	.68	57.8
3900.0000	.39	35.4
4000.0000	.37	14.0
4100.0000	.23	-8.2
4200.0000	.22	-30.3
4300.0000	.30	-52.6
4400.0000	.30	-74.1
4500.0000	.46	-97.0
4600.0000	.56	-119.6
4700.0000	.75	-144.5
4800.0000	.94	-171.7
4900.0000	1.19	158.4
5000.0000	1.35	124.3
5100.0000	1.36	86.0
5200.0000	1.16	41.1
5300.0000	.82	-5.5
5400.0000	.64	-48.6
5500.0000	.54	-86.9
5600.0000	.62	-120.4
5700.0000	.69	-148.2
5800.0000	.80	-173.4
5900.0000	.91	164.3
6000.0000	1.02	144.2

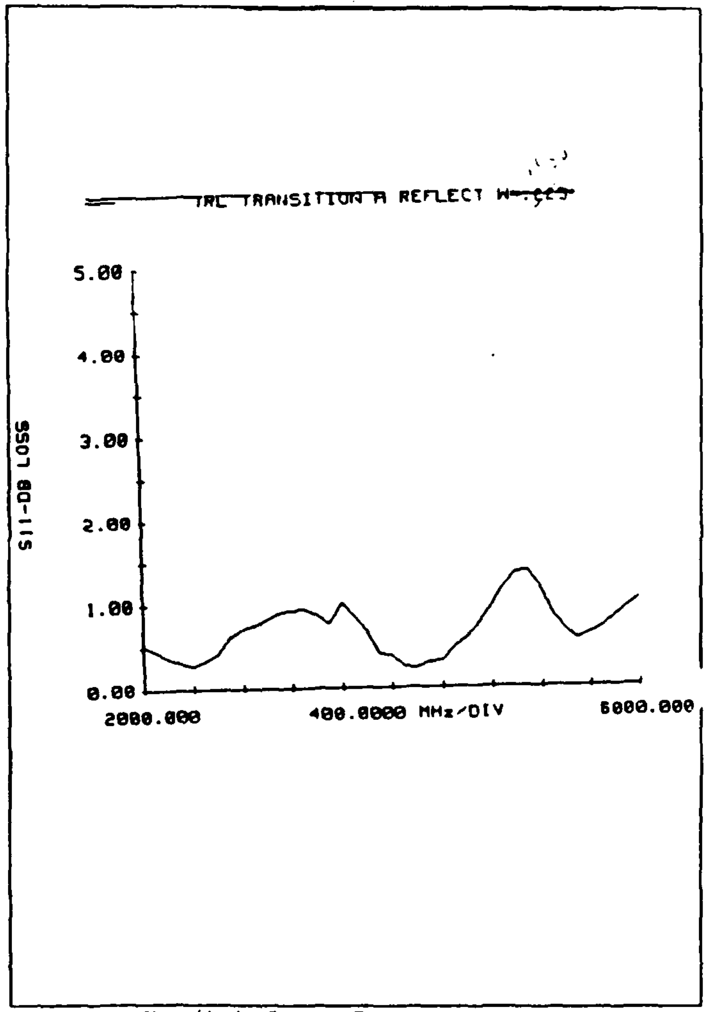
Reflect Parameters TRL transition A. W=.450"

Table 20. MEASURED REFLECT S-PARAMETERS OF TRL TRANSITION B W= .450"

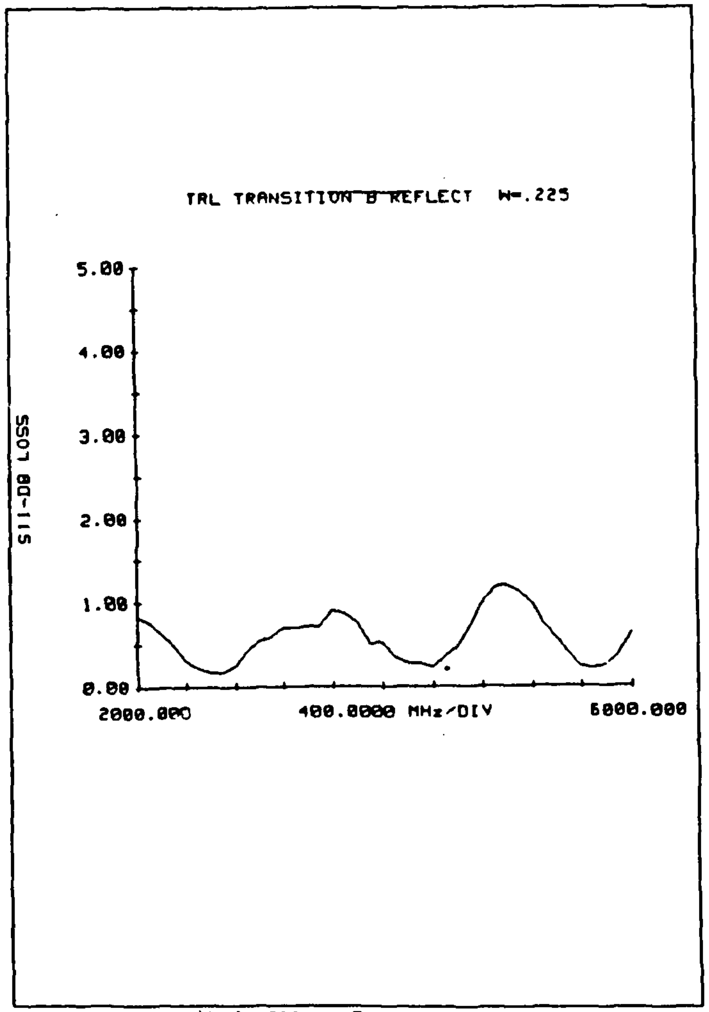
TRL TRANSITION B REFLECT W=.225

FREQUENCY MHz	RETURN LOSS-IN S11 DB	ANG
2000.0000	.83	-151.3
2100.0000	.76	-178.4
2200.0000	.62	153.5
2300.0000	.47	124.8
2400.0000	.31	96.3
2500.0000	.21	66.2
2600.0000	.17	36.5
2700.0000	.16	6.1
2800.0000	.23	-23.4
2900.0000	.41	-52.1
3000.0000	.53	-80.7
3100.0000	.59	-108.2
3200.0000	.68	-135.1
3300.0000	.70	-161.2
3400.0000	.71	174.9
3500.0000	.70	150.6
3600.0000	.69	127.0
3700.0000	.86	106.6
3800.0000	.76	85.2
3900.0000	.50	63.9
4000.0000	.52	42.9
4100.0000	.33	21.5
4200.0000	.28	-1.1
4300.0000	.27	-24.6
4400.0000	.22	-48.6
4500.0000	.33	-75.1
4600.0000	.45	-101.6
4700.0000	.71	-130.3
4800.0000	.96	-160.4
4900.0000	1.16	168.4
5000.0000	1.19	135.8
5100.0000	1.12	103.4
5200.0000	.98	69.5
5300.0000	.72	36.4
5400.0000	.54	3.7
5500.0000	.38	-27.6
5600.0000	.22	-57.6
5700.0000	.20	-86.8
5800.0000	.24	-115.1
5900.0000	.36	-141.9
6000.0000	.62	-167.1

Reflect Parameters TRL transition B W=.450"



Magnitude S11 v. Frequency



Magnitude S11 v. Frequency

Figure 46. S11 v. Frequency

W = .450"

Table 21. MEASURED REFLECT S-PARAMETERS OF TRL TRANSITION

A W= .300"

TRL TRANSITION A REFLECT W=.300

FREQUENCY MHz	RETURN LOSS-IN S11 DB	ANG
2000.0000	.27	169.3
2100.0000	.18	138.4
2200.0000	.10	109.4
2300.0000	.12	81.3
2400.0000	.07	54.8
2500.0000	.18	27.4
2600.0000	.15	1.4
2700.0000	.27	-23.8
2800.0000	.40	-49.6
2900.0000	.55	-74.0
3000.0000	.77	-99.9
3100.0000	1.06	-124.9
3200.0000	1.33	-149.3
3300.0000	1.56	-173.1
3400.0000	1.67	164.6
3500.0000	1.59	141.0
3600.0000	1.65	117.3
3700.0000	1.34	95.8
3800.0000	.98	71.6
3900.0000	.54	47.2
4000.0000	.47	23.1
4100.0000	.25	-1.6
4200.0000	.24	-26.6
4300.0000	.33	-51.9
4400.0000	.26	-77.1
4500.0000	.44	-104.1
4600.0000	.50	-132.0
4700.0000	.64	-163.8
4800.0000	.86	160.8
4900.0000	1.01	123.5
5000.0000	1.06	82.7
5100.0000	.91	41.7
5200.0000	.63	1.4
5300.0000	.42	-35.7
5400.0000	.28	-67.6
5500.0000	.19	-97.0
5600.0000	.26	-124.0
5700.0000	.36	-147.5
5800.0000	.50	-170.0
5900.0000	.67	169.7
6000.0000	.85	151.0

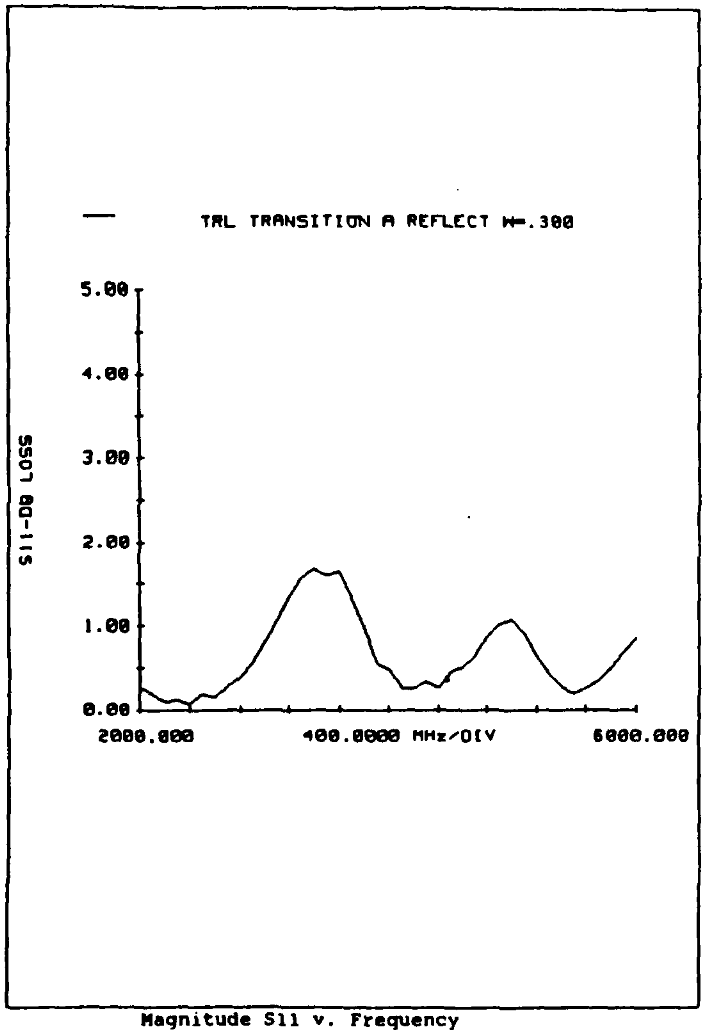
Reflect Parameters TRL transition A w=.300"

Table 22. MEASURED REFLECT S-PARAMETERS OF TRL TRANSITION

B W= .300"

FREQUENCY MHz	RETURN LOSS-IN S11 DB	ANG
2000.0000	.14	-169.6
2100.0000	.04	162.4
2200.0000	.00	135.1
2300.0000	.01	108.4
2400.0000	-.00	82.8
2500.0000	.03	56.2
2600.0000	.14	30.8
2700.0000	.16	5.5
2800.0000	.19	-19.1
2900.0000	.25	-43.0
3000.0000	.24	-67.0
3100.0000	6.13	-90.0
3200.0000	.26	-114.9
3300.0000	.27	-1[illegible].7
3400.0000	.32	-161.1
3500.0000	.28	175.5
3600.0000	.40	151.4
3700.0000	.52	129.1
3800.0000	.53	105.7
3900.0000	.40	81.8
4000.0000	.50	57.6
4100.0000	.33	33.2
4200.0000	.34	7.4
4300.0000	.28	-19.7
4400.0000	.15	-47.2
4500.0000	.17	-77.2
4600.0000	.15	-106.8
4700.0000	.22	-138.4
4800.0000	.34	-171.2
4900.0000	.54	156.2
5000.0000	.67	123.7
5100.0000	.83	92.8
5200.0000	1.12	63.4
5300.0000	.68	35.9
5400.0000	.49	7.8
5500.0000	.35	-18.4
5600.0000	.13	-43.4
5700.0000	.05	-67.8
5800.0000	-.02	-91.8
5900.0000	.02	-115.7
6000.0000	.17	-139.6

Reflect Parameters TRL transition B w=.300"



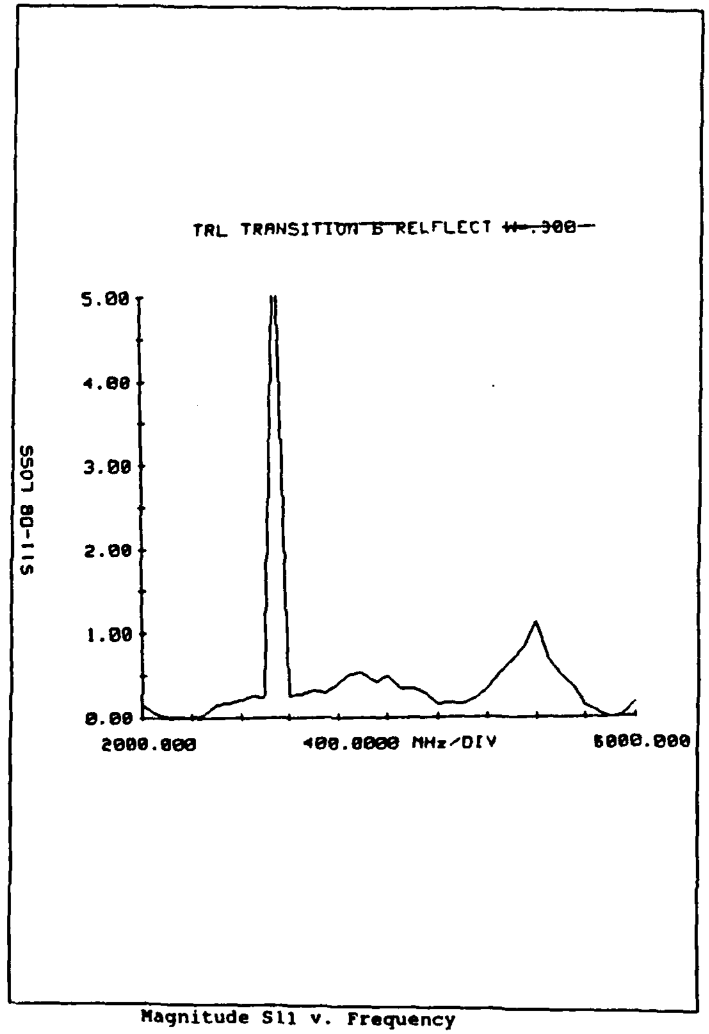


Figure 47. S11 v. Frequency

W = .300"

Table 23. MEASURED REFLECT S-PARAMETERS OF TRL TRANSITION

A W= .225"

TRL TRANSITION A REFLECT W=.225

FREQUENCY	RETURN LOSS-IN S11	
MHz	DB	ANG
2000.0000	.33	141.3
2100.0000	.21	114.7
2200.0000	.32	91.1
2300.0000	.22	67.4
2400.0000	.09	45.6
2500.0000	.10	22.8
2600.0000	.16	.4
2700.0000	.23	-21.2
2800.0000	.36	-44.4
2900.0000	.48	-66.3
3000.0000	.67	-90.4
3100.0000	.78	-113.7
3200.0000	.83	-138.6
3300.0000	.83	-164.2
3400.0000	.82	170.3
3500.0000	.80	143.3
3600.0000	1.00	116.2
3700.0000	1.03	92.2
3800.0000	.81	65.6
3900.0000	.46	37.4
4000.0000	.39	8.2
4100.0000	.26	-23.8
4200.0000	.33	-57.0
4300.0000	.48	-90.9
4400.0000	.61	-124.6
4500.0000	.87	-157.8
4600.0000	.95	169.9
4700.0000	.97	139.0
4800.0000	.97	108.9
4900.0000	.78	81.2
5000.0000	.73	51.9
5100.0000	.57	23.7
5200.0000	.40	-5.5
5300.0000	.28	-35.2
5400.0000	.22	-63.8
5500.0000	.21	-93.0
5600.0000	.36	-121.6
5700.0000	.50	-146.9
5800.0000	.65	-171.3
5900.0000	.72	166.8
6000.0000	.86	146.2

Reflect Parameters TRL transition A w=.225"

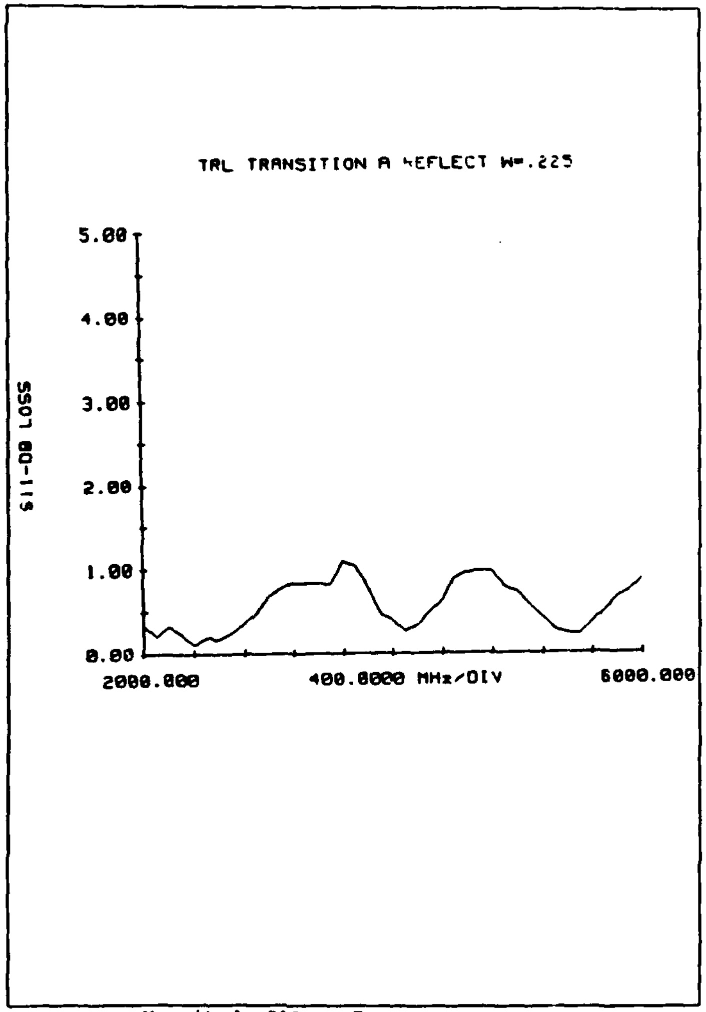
Table 24. MEASURED REFLECT S-PARAMETERS OF TRL TRANSITION

B W= .225"

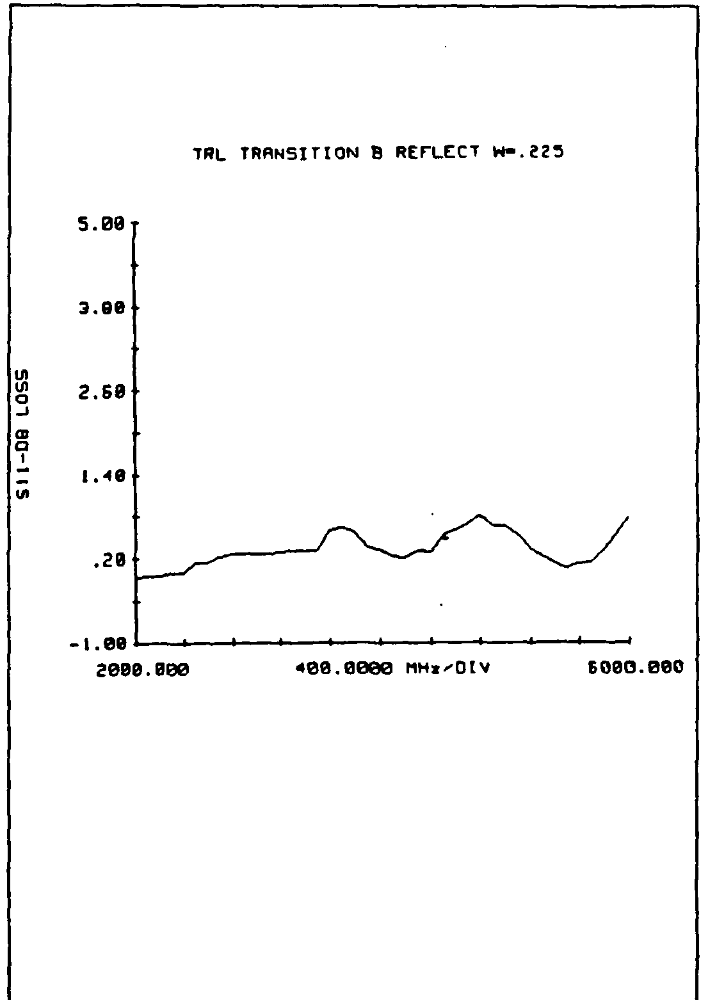
TRL TRANSITION B REFLECT W=.225

FREQUENCY	RETURN LOSS-IN S11	
MHz	DB	ANG
2000.0000	-.06	141.4
2100.0000	-.04	115.4
2200.0000	-.04	91.2
2300.0000	-.00	67.5
2400.0000	-.01	45.2
2500.0000	.14	22.0
2600.0000	.14	-.1
2700.0000	.23	-21.5
2800.0000	.25	-43.8
2900.0000	.26	-64.9
3000.0000	.27	-88.0
3100.0000	.27	-111.2
3200.0000	.27	-135.4
3300.0000	.31	-160.7
3400.0000	.30	174.2
3500.0000	.30	146.4
3600.0000	.60	117.1
3700.0000	.64	89.8
3800.0000	.57	59.4
3900.0000	.35	27.9
4000.0000	.32	-3.8
4100.0000	.21	-37.4
4200.0000	.20	-70.5
4300.0000	.30	-102.7
4400.0000	.29	-134.5
4500.0000	.51	-165.6
4600.0000	.60	163.5
4700.0000	.67	133.2
4800.0000	.80	103.2
4900.0000	.66	75.0
5000.0000	.66	45.0
5100.0000	.53	16.7
5200.0000	.33	-11.4
5300.0000	.22	-38.0
5400.0000	.12	-64.1
5500.0000	.05	-89.4
5600.0000	.11	-114.2
5700.0000	.14	-137.2
5800.0000	.30	-160.4
5900.0000	.51	177.7
6000.0000	.76	157.1

Reflect Parameters TRL transition B w=.225"



Magnitude S11 v. Frequency



Magnitude S11 v. Frequency

Figure 48. S11 v. Frequency

W = .225" .

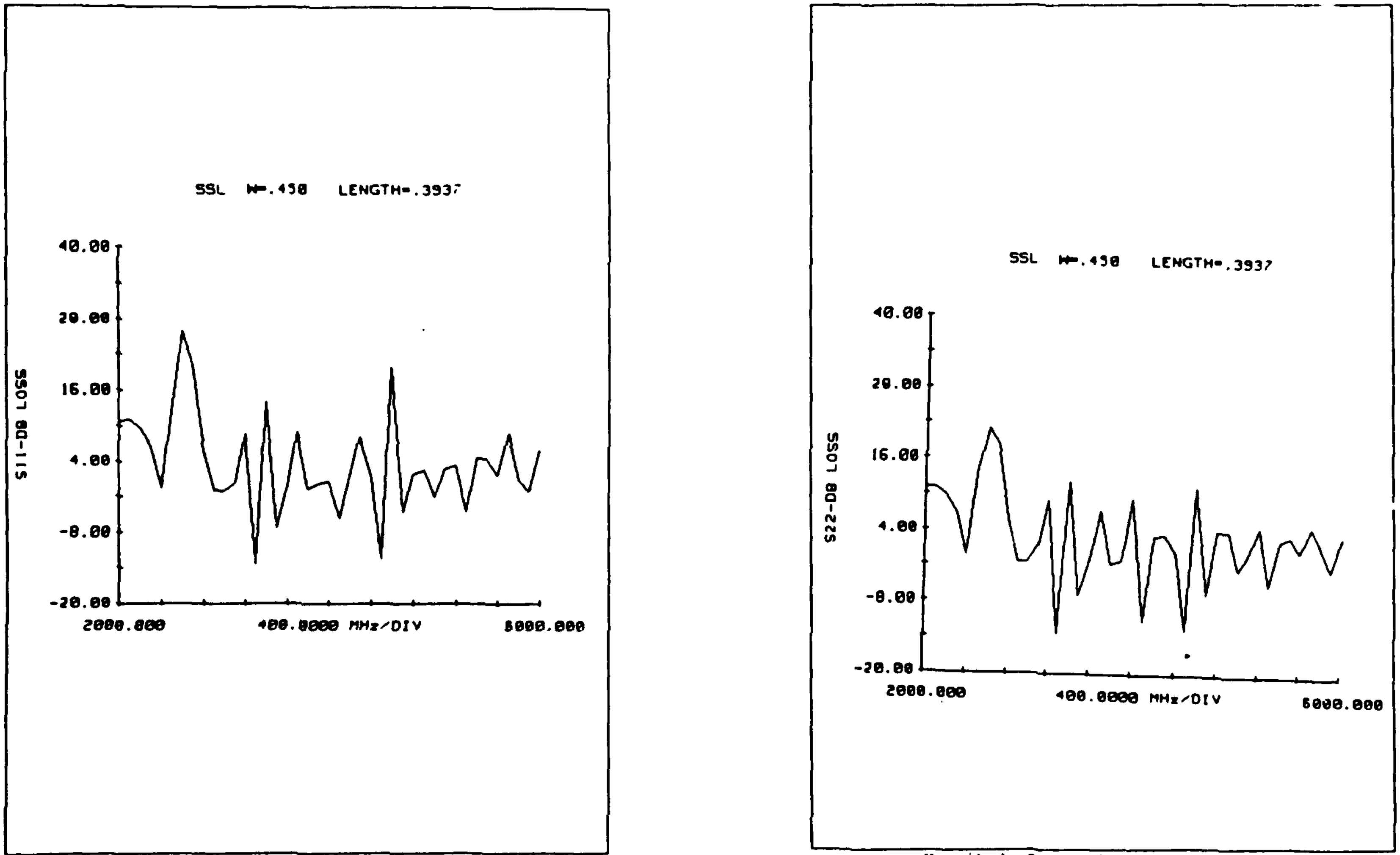
Table 25. MEASURED S-PARAMETERS WITH ADDED LENGTH

W= .450" La= .3937"

SSL W=.450 LENGTH=.3937

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-OU S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	10.84	55.3	-1.35	130.4	.0006	2.57	141.1	11.06	39.7
2100.0000	10.93	27.2	-1.49	118.1	.0006	2.88	121.7	10.90	14.7
2200.0000	9.51	9.0	-1.70	95.1	.0006	3.01	99.1	9.77	-2.0
2300.0000	6.45	-12.4	-1.55	74.9	.0096	3.53	88.5	6.82	-22.2
2400.0000	-.76	-14.1	-.81	87.8	.0030	6.11	107.8	-.33	-27.5
2500.0000	12.33	92.3	-1.17	-19.2	.0003	1.70	-16.7	13.33	58.4
2600.0000	25.89	-107.1	-1.43	-29.7	.0006	2.38	-26.4	20.93	-72.5
2700.0000	20.06	-129.9	-1.67	-51.7	.0015	2.54	-47.9	18.32	-115.7
2800.0000	5.59	93.2	-1.43	-105.2	.0087	-.17	-44.1	5.87	95.5
2900.0000	-.97	-77.7	-5.87	-59.3	.0042	-3.79	-117.2	-1.41	-78.4
3000.0000	-1.09	50.4	1.20	148.1	.0076	4.86	-28.2	-1.26	52.6
3100.0000	.37	3.8	7.96	-126.1	.0093	12.54	-44.3	1.54	5.9
3200.0000	8.57	133.7	.24	-102.6	.0012	4.98	179.3	9.16	130.6
3300.0000	-13.44	-67.5	-14.97	-147.5	.0033	-10.93	7.8	-13.49	-67.0
3400.0000	13.84	99.0	-1.21	94.8	.0092	1.49	124.2	12.16	101.1
3500.0000	-7.40	-98.9	-10.13	123.8	.0036	-7.86	34.3	-6.96	-104.2
3600.0000	-.30	70.0	.64	-6.9	.0089	2.83	154.7	-.79	65.8
3700.0000	8.89	24.3	1.02	31.9	.0037	4.90	88.2	7.44	34.8
3800.0000	-.77	38.3	7.70	-100.1	.0053	12.70	-126.6	-1.62	33.5
3900.0000	.11	-2.8	7.06	67.9	.0043	9.60	-106.7	-.85	10.9
4000.0000	.61	76.4	-4.27	-87.3	.0002	5.12	-20.1	9.50	54.0
4100.0000	-5.62	-169.3	-16.98	-96.2	.0021	-2.63	169.9	-11.15	-130.2
4200.0000	1.63	33.8	3.60	-173.4	.0005	15.47	-50.6	3.37	47.0
4300.0000	8.10	48.1	4.36	167.2	.0084	6.42	175.2	3.55	45.9
4400.0000	1.41	-2.8	4.90	-135.1	.0011	9.34	98.4	.65	-1.2
4500.0000	-12.61	-111.0	-15.53	-175.6	.0018	-9.81	-49.6	-12.68	-98.3
4600.0000	19.83	70.0	-2.54	120.6	.0027	5.04	129.7	11.35	-51.6
4700.0000	-4.69	110.6	-10.43	24.4	.0000	1.25	-104.1	-6.49	145.7
4800.0000	1.80	23.0	7.05	23.7	.0096	17.00	109.7	4.35	31.5
4900.0000	2.52	-1.4	4.82	37.7	.0100	9.40	-36.8	4.35	-18.6
5000.0000	-2.13	-37.3	.49	38.4	.0020	2.37	-150.3	-2.26	-59.7
5100.0000	2.68	-115.8	-.78	-33.7	.0001	.06	33.9	.45	-154.0
5200.0000	3.25	-84.0	1.04	-38.0	.0012	2.20	-79.9	5.03	-123.5
5300.0000	-4.70	-149.0	-4.07	-81.1	.0011	-3.30	125.8	-4.79	-170.5
5400.0000	4.51	142.4	.46	-121.2	.0002	2.95	-22.0	2.77	125.0
5500.0000	4.26	-177.2	-3.66	-127.7	.0015	1.66	-143.2	3.53	172.0
5600.0000	1.63	33.3	10.44	170.2	.0006	16.94	53.0	1.00	30.5
5700.0000	8.68	-124.2	-4.74	155.3	.0015	4.55	-161.2	5.23	-152.9
5800.0000	.81	-126.6	-4.77	101.1	.0004	1.85	30.5	1.86	-153.7
5900.0000	-1.13	-150.3	-.22	86.3	.0006	.24	-102.7	-2.17	152.2
6000.0000	5.87	-172.6	3.06	65.1		3.08	120.8	3.62	119.3

Measure S-parameters with added length. La=.3937" W=.450"

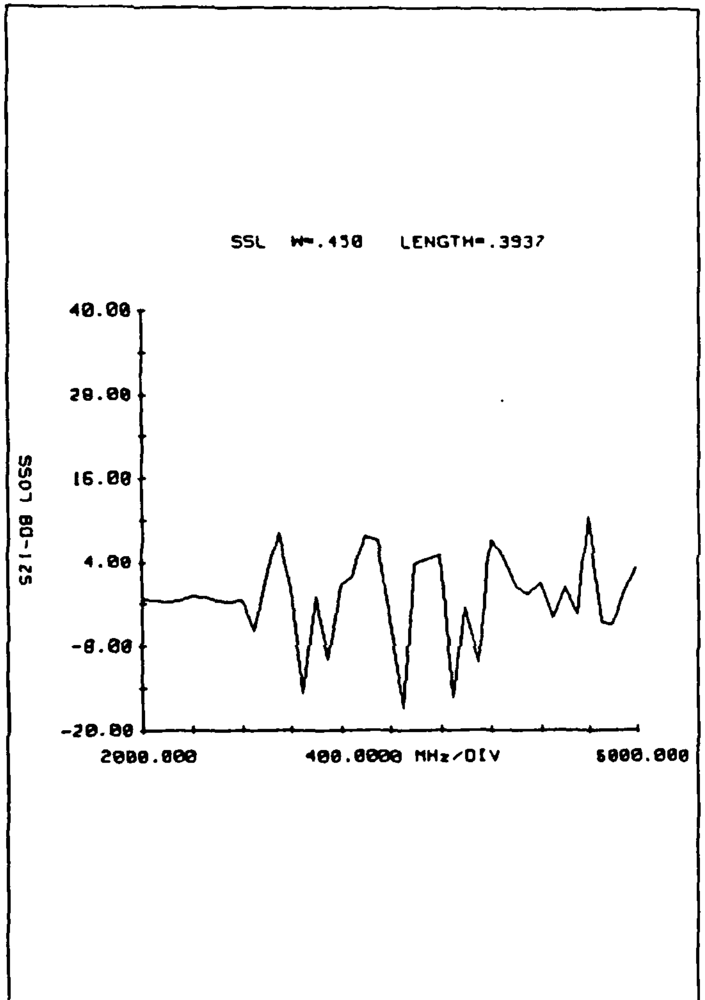


Magnitude S11 v. Frequency

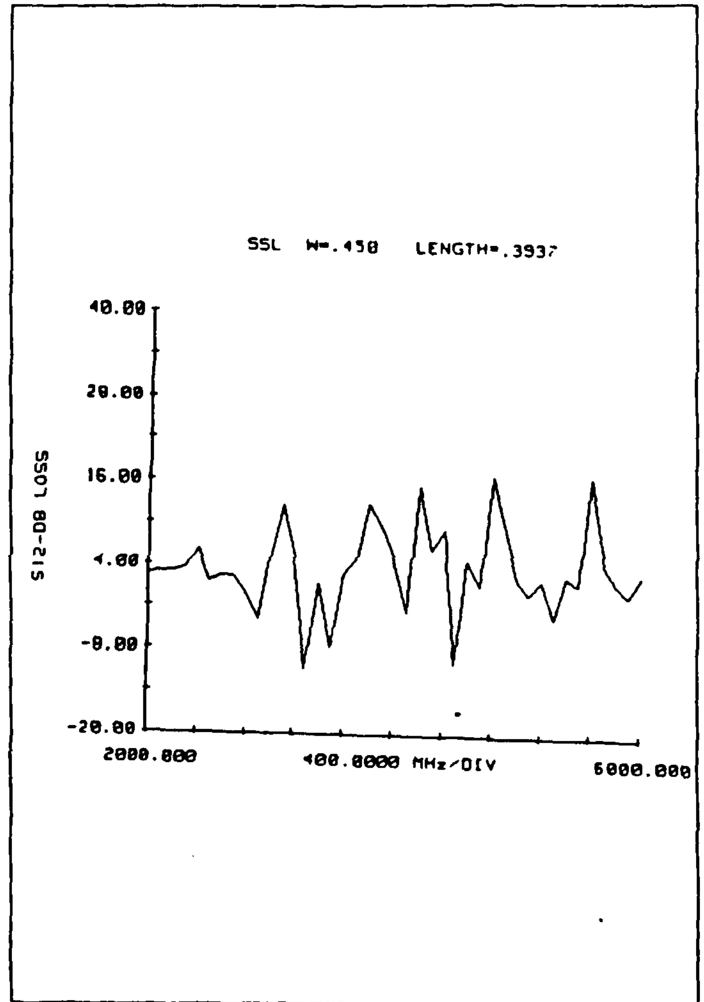
Magnitude S22 v. Frequency

Figure 49. S11,S22 v. Frequency

W = .450" La= .3937"



Magnitude S21 v. Frequency



Magnitude S12 v. Frequency

Figure 50. S21,S12 v. Frequency

W = .450" La= .3937"

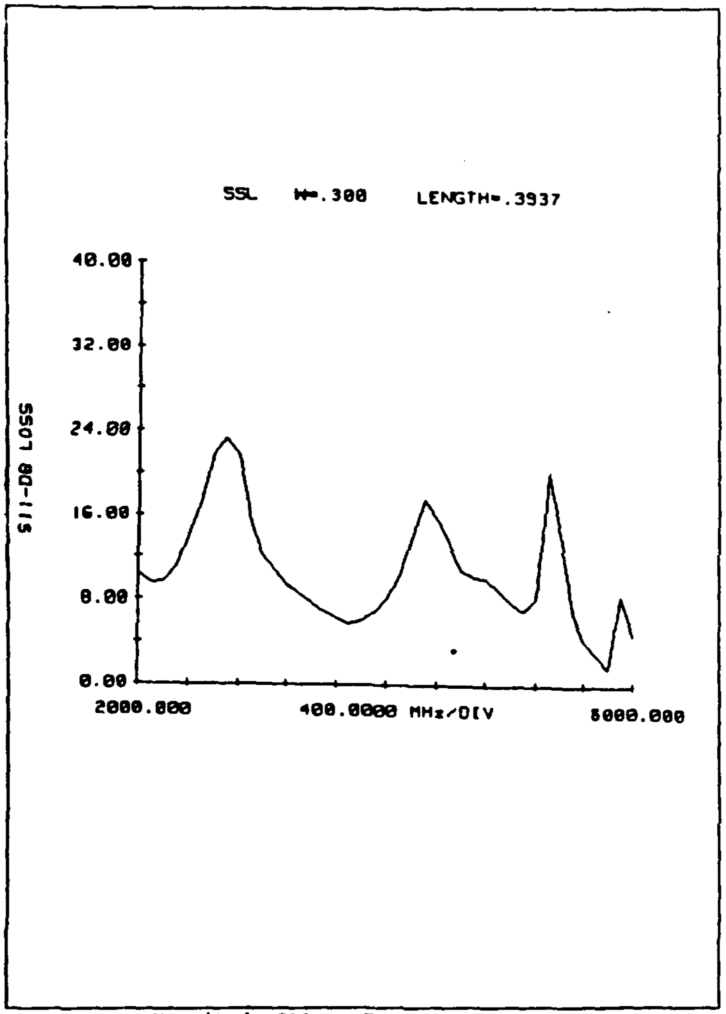
Table 26. MEASURED S-PARAMETERS WITH ADDED LENGTH

W= .300" La= .3937"

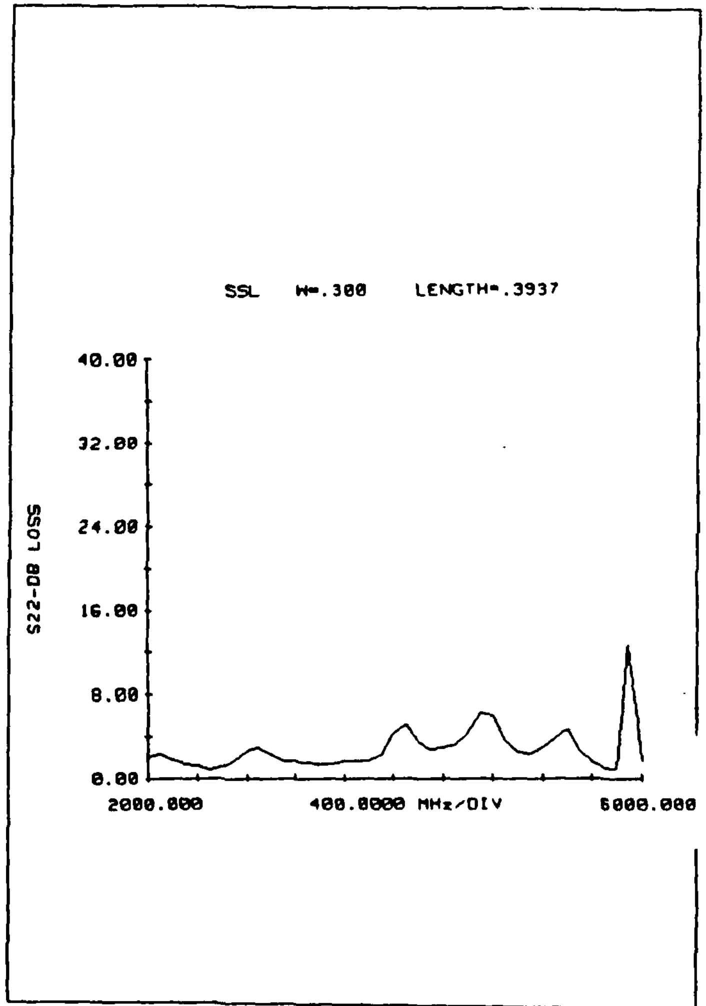
SSL W=.300 LENGTH=.3937

FREQUENCY	RETURN LOSS-IN		LOSS-FORWARD			LOSS-REVERSE		RETURN LOSS-O	
	S11		S21		DELAY	S12		S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	10.31	44.3	.42	152.4	.0008	7.77	-103.2	2.01	-3.
2100.0000	9.58	12.5	.67	125.2	.0008	6.52	-97.8	2.26	-66.
2200.0000	9.66	-11.2	.55	97.7	.0008	7.62	169.8	1.75	-164.
2300.0000	11.03	-33.9	-.40	67.9	.0009	8.37	175.0	1.36	114.
2400.0000	14.02	-58.2	.25	36.9	.0008	9.16	177.5	1.24	102.
2500.0000	17.23	-97.2	.13	9.0	.0008	9.00	82.4	.63	29.
2600.0000	21.76	-159.1	.28	-19.9	.0008	8.69	87.1	1.02	-48.
2700.0000	23.35	116.3	29.76	-58.3	.0007	8.18	93.3	1.54	-43.
2800.0000	21.62	45.5	30.59	-75.7	.0052	6.41	-.3	2.63	-128.
2900.0000	15.25	-6.0	24.96	96.6	.0025	6.10	3.1	2.92	150.
3000.0000	12.28	-33.8	21.01	6.6	.0025	6.64	7.2	2.31	65.-
3100.0000	10.78	-64.7	20.15	-82.9	.0049	8.63	-84.5	1.61	-18.
3200.0000	9.39	-93.0	19.11	98.9	.0026	9.38	-170.3	1.53	-9.
3300.0000	8.63	-120.6	18.73	5.8	.0050	9.72	-33.1	1.41	-96.-
3400.0000	7.73	-150.1	17.36	-172.4	.0023	10.64	-172.6	1.38	176.
3500.0000	6.85	-178.7	16.48	105.4	.0026	10.17	-168.0	1.28	-171.
3600.0000	6.27	156.0	15.58	12.3	.0024	9.72	-166.1	1.67	-168.
3700.0000	5.85	130.5	14.82	-72.5	.0050	8.88	100.8	1.63	108.
3800.0000	5.99	105.9	15.40	106.8	.0025	6.90	107.6	1.64	28.
3900.0000	6.89	81.1	16.77	16.9	.0049	5.33	108.3	2.23	28.1
4000.0000	8.16	54.7	18.01	-159.0	.0025	3.23	15.0	4.17	-53.
4100.0000	10.40	29.3	20.15	110.8	.0024	2.47	17.3	5.15	-135.7
4200.0000	13.94	6.3	23.74	25.6	.0025	3.51	22.6	3.58	140.7
4300.0000	17.62	28.1	27.16	-65.8	.0025	4.34	-69.0	2.73	55.4
4400.0000	15.63	59.1	24.93	-155.2	.0026	4.68	-66.7	2.84	66.9
4500.0000	13.37	60.0	22.69	112.0	.0022	3.62	-61.9	3.12	-21.6
4600.0000	10.95	49.9	19.97	32.8	.0026	2.54	-153.6	4.06	-103.9
4700.0000	10.21	37.0	19.61	-62.0	.0049	1.40	-148.7	6.16	-179.7
4800.0000	10.15	14.9	19.17	122.7	.0024	1.62	-147.2	5.95	100.3
4900.0000	9.04	.1	18.39	36.4	.0026	3.17	124.6	3.57	12.5
5000.0000	7.83	-18.5	18.02	-56.4	.0048	4.57	39.3	2.45	-75.9
5100.0000	6.99	-48.7	16.67	130.8	.0026	4.84	50.0	2.31	-64.0
5200.0000	8.33	-84.1	17.92	38.5	.0043	4.34	37.8	2.88	-146.6
5300.0000	20.22	-121.5	29.17	-117.3	.0083	3.73	-45.8	3.65	130.0
5400.0000	13.77	9.9	24.10	-57.5	.0048	2.78	-47.3	4.69	134.8
5500.0000	7.08	-34.0	16.81	128.0	.0023	4.51	-46.2	2.64	-42.6
5600.0000	4.22	-71.6	14.05	46.5	.0047	8.61	-132.3	1.55	-41.9
5700.0000	2.87	-111.0	13.12	-122.3	.0028	11.03	-128.9	.96	-114.3
5800.0000	1.60	-159.9	11.55	135.2	.0076	16.43	-174.9	.06	152.9
5900.0000	8.52	22.4	19.28	-136.8	.0073	2.50	-133.3	12.62	174.0
6000.0000	4.76	-147.6	14.46	-48.9		7.06	-124.8	1.55	175.0

Measure S-parameters with added length. La=.3937" w=.300"



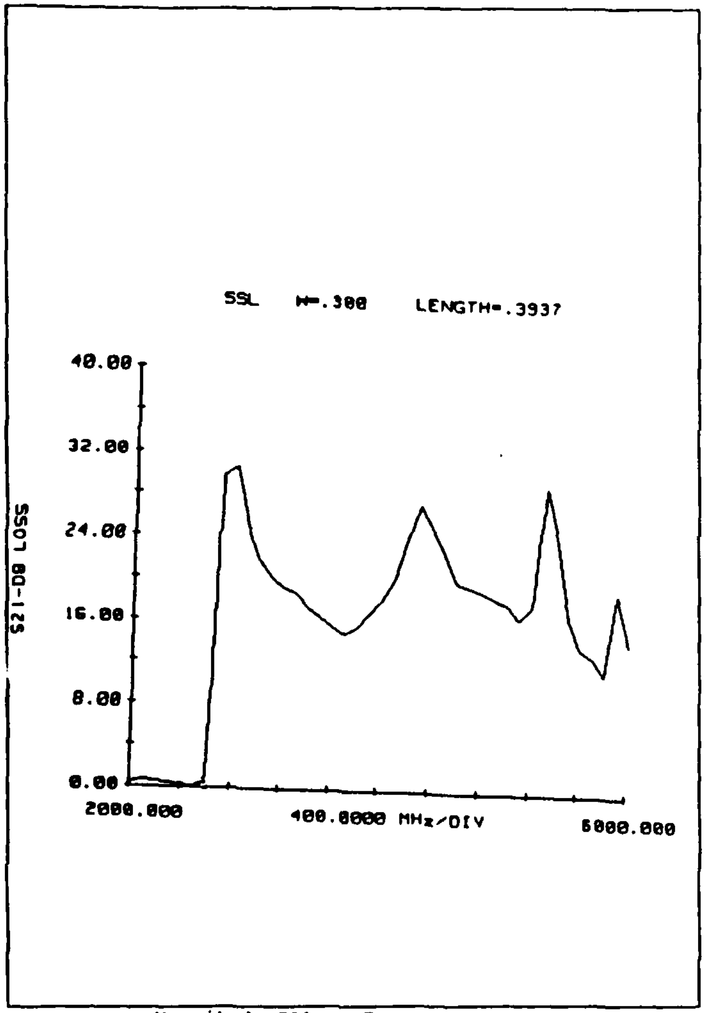
Magnitude S11 v. Frequency



Magnitude S22 v. Frequency

Figure 51. S11,S22 v. Frequency

W = .300" La= .3937"



Magnitude S21 v. Frequency

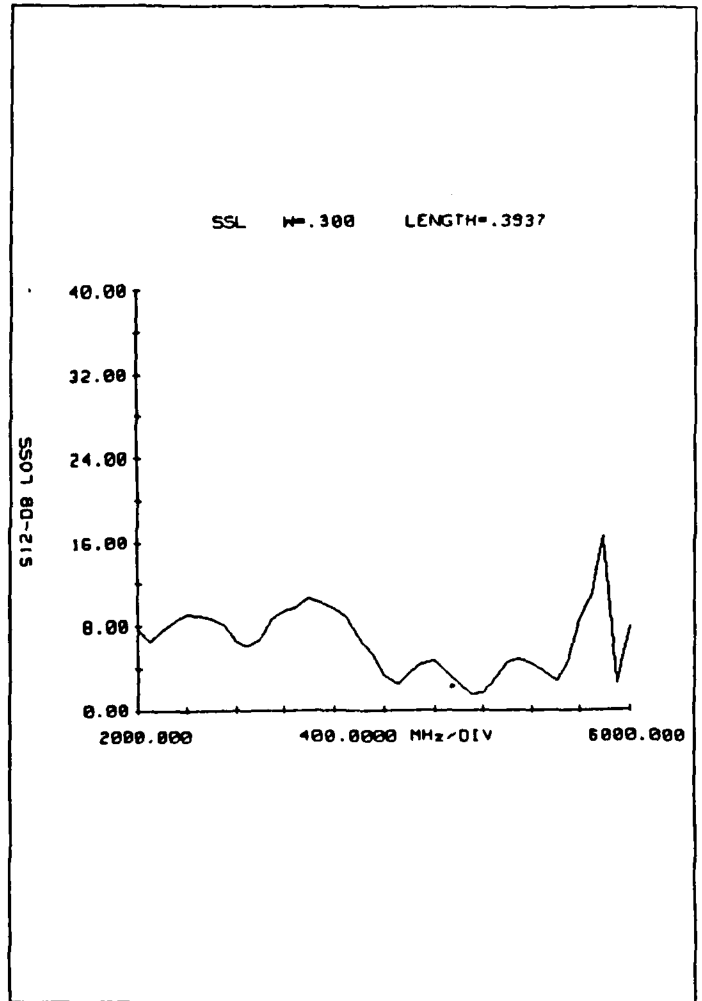


Figure 103. Magnitude S12 v. Frequency

Figure 52. S21,S12 v. Frequency

W = .300" La= .3937"

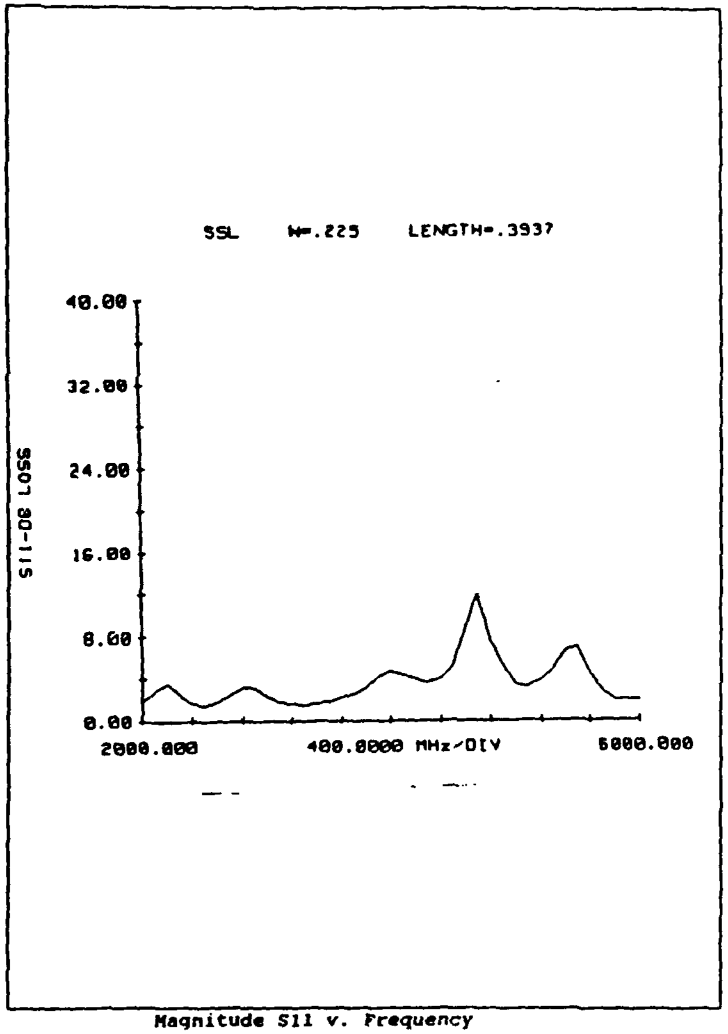
Table 27. MEASURED S-PARAMETERS WITH ADDED LENGTH

W= .225"   La= .3937"

SSL   W=.225   LENGTH=.3937

FREQUENCY	RETURN LOSS-IN S11		LOSS-FORWARD S21		DELAY	LOSS-REVERSE S12		RETURN LOSS-O S22	
MHz	DB	ANG	DB	ANG	u-SEC	DB	ANG	DB	ANG
2000.0000	1.79	-19.6	5.63	-120.2	.0010	.62	171.4	7.92	86.
2100.0000	2.86	-95.3	3.29	-154.6	.0012	.81	172.0	7.31	100.
2200.0000	3.48	168.2	3.47	163.9	.0011	.75	171.6	7.63	7.
2300.0000	2.40	89.0	4.44	125.2	.0009	.43	86.7	9.08	21.
2400.0000	1.64	35.0	5.70	93.4	.0007	.57	85.0	12.03	-53.
2500.0000	1.48	-10.7	5.67	69.9	.0007	.32	83.2	16.76	-55.
2600.0000	1.69	-57.3	5.36	44.3	.0008	.31	-.3	23.04	-33.
2700.0000	2.47	-108.1	4.46	15.7	.0009	.22	.9	23.67	34.
2800.0000	3.16	-177.5	3.12	-15.3	.0011	-.02	-.4	18.70	-35.
2900.0000	3.14	97.6	3.24	-53.3	.0010	.14	-85.6	12.52	-29.
3000.0000	2.35	22.5	4.44	-89.2	.0008	.49	-84.2	9.35	-22.
3100.0000	1.80	-31.6	6.63	-118.3	.0008	.87	-85.4	8.10	-17.
3200.0000	1.58	-78.2	7.19	-147.1	.0006	1.07	-169.5	7.47	-100.
3300.0000	1.43	-116.0	7.49	-168.0	.0904	1.44	-169.7	7.50	-97.
3400.0000	1.58	-152.9	7.54	175.8	.0005	1.39	-171.2	7.70	-175.
3500.0000	1.67	166.9	6.84	157.2	.0007	.93	104.1	7.68	-172.
3600.0000	2.09	126.0	6.11	131.6	.0007	.70	102.6	8.28	-170.
3700.0000	2.40	81.1	4.96	107.0	.0008	.71	100.7	8.03	107.
3800.0000	2.93	23.9	3.26	78.0	.0011	.60	17.3	9.06	115.
3900.0000	4.10	-44.6	2.53	39.4	.0010	.41	17.5	11.52	28.
4000.0000	4.64	-122.2	1.88	3.6	.0009	.28	17.1	14.11	39.
4100.0000	4.27	165.5	2.06	-29.2	.0007	.18	-67.4	16.40	-50.
4200.0000	3.94	111.5	2.62	-55.3	.0007	.28	-66.3	14.98	-136.
4300.0000	3.53	62.4	2.74	-80.4	.0009	.62	-69.4	15.16	146.
4400.0000	3.93	12.0	2.03	-111.9	.0008	.73	-156.4	11.02	83.
4500.0000	5.04	-36.5	1.15	-142.1	.0009	.69	-154.4	8.96	63.
4600.0000	8.45	-97.4	.59	-173.9	.0010	.68	-153.8	7.78	80.
4700.0000	11.83	157.4	.42	149.9	.0010	.61	124.3	8.17	-.
4800.0000	7.66	61.8	.88	112.1	.0006	.85	123.5	8.48	10.
4900.0000	4.89	1.6	1.97	82.1	.0076	.75	124.4	8.28	-74.
5000.0000	3.47	-45.1	12.75	168.5	.0011	.95	39.0	8.83	-77.
5100.0000	3.16	-86.0	12.82	129.8	.0026	.53	39.1	10.37	-63.
5200.0000	3.85	-123.8	13.35	37.4	.0049	.36	39.2	14.68	-134.
5300.0000	4.79	-176.9	14.56	-137.9	.0049	.54	-44.7	26.90	150.
5400.0000	6.54	119.3	16.23	43.9	.0050	.31	-46.9	24.58	-30.
5500.0000	6.87	23.6	16.85	-136.9	.0049	.61	-47.5	15.74	-55.
5600.0000	4.38	-55.4	13.94	47.4	.0039	1.32	-132.6	11.01	-118.
5700.0000	2.75	-109.7	12.57	-92.1	.0037	2.15	-130.1	7.57	-112.
5800.0000	1.92	-146.9	11.85	135.1	.0048	3.28	-133.6	4.72	-114.
5900.0000	1.91	-177.2	11.91	-38.3	.0024	3.21	142.4	4.14	-124.
6000.0000	1.87	154.1	11.39	-124.6		2.92	143.3	3.83	176.

Measure S-parameters with added length. La=.3937" W=.225"



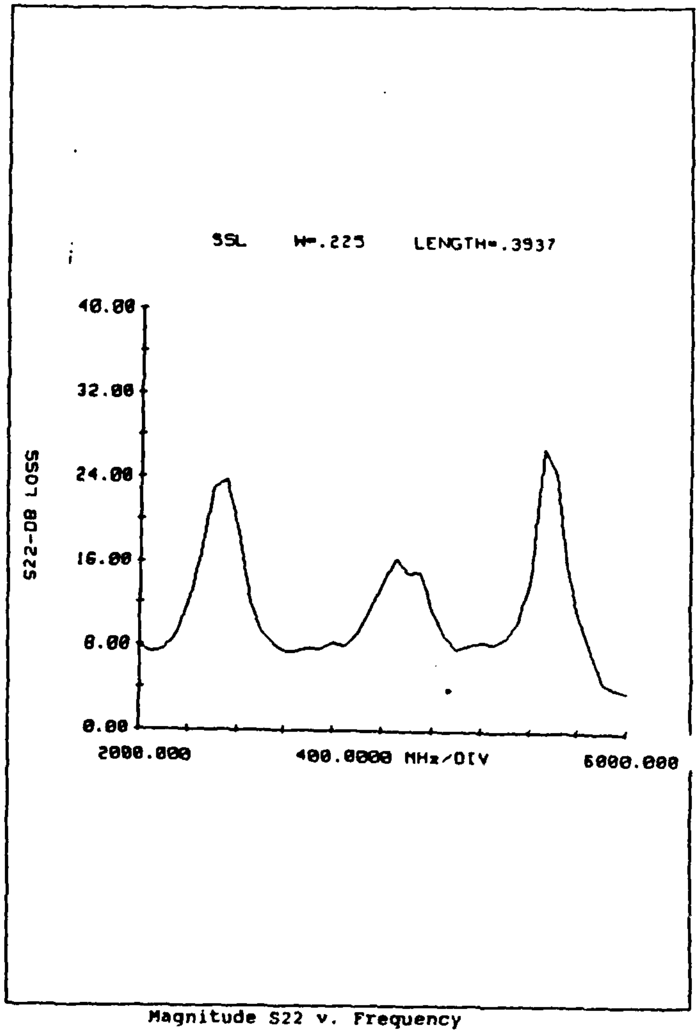
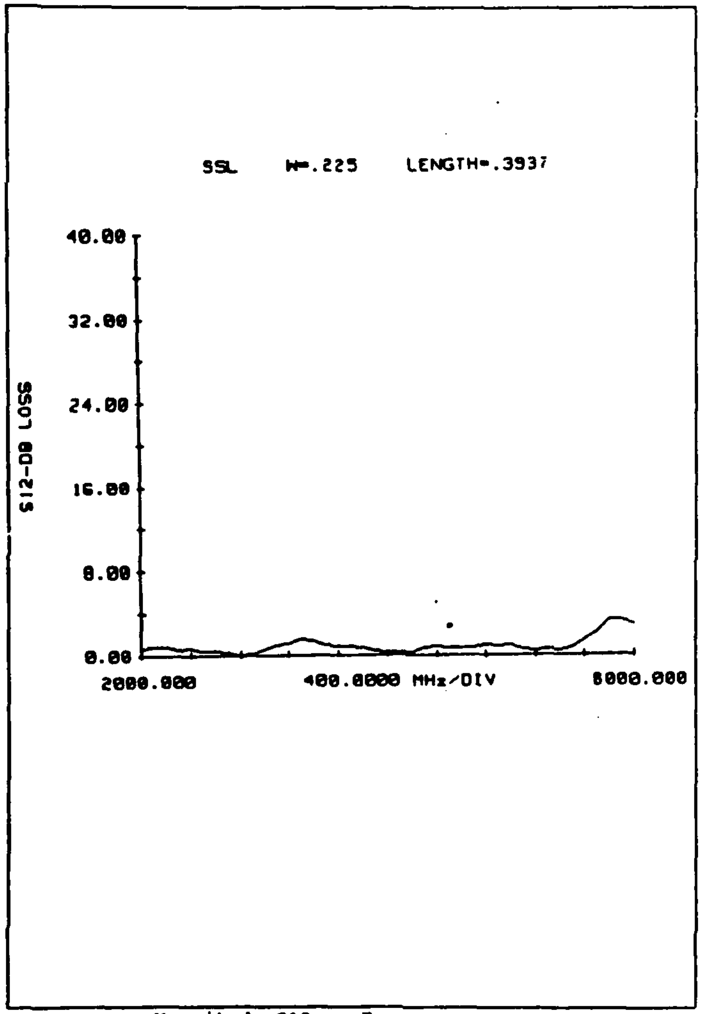
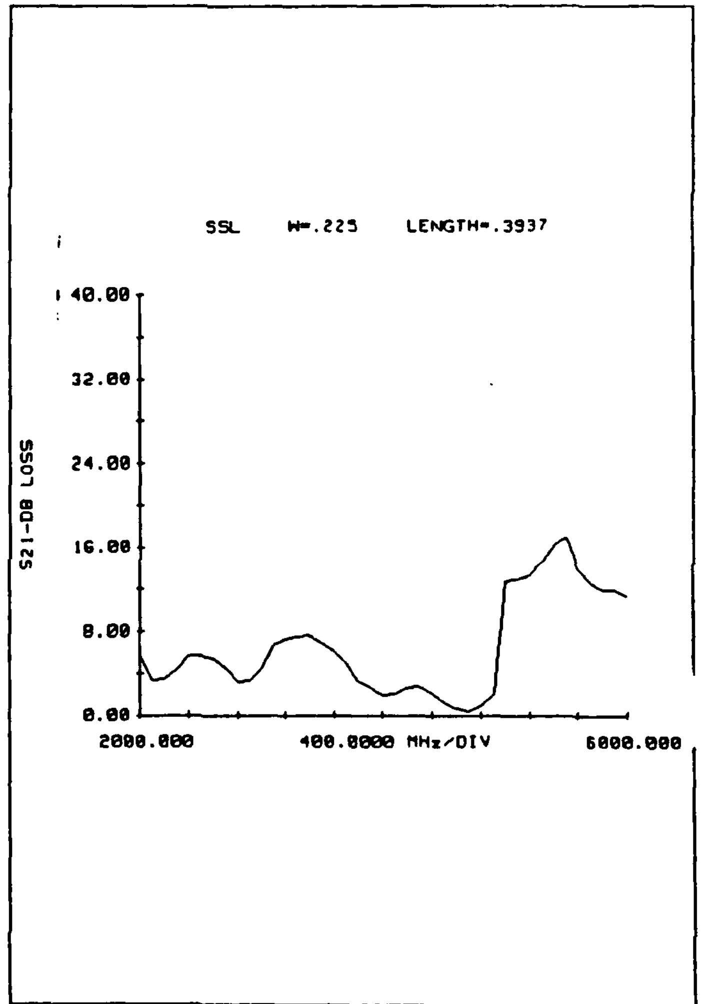


Figure 53. S11,S22 v. Frequency

w = .225" La= .3937"



Magnitude S12 v. Frequency



Magnitude S21 v. Frequency

Figure 54. S21,S12 v. Frequency

W = .225" La= .3937"

Table 28. DE-EMBEDDED S-PARAMETERS W= .450" G=.225"

Freq (GHz)	S11 dB	A11 °'s	S12 dB	A12 °'s	S21 dB	A21 °'s	S22 dB	A22 °'s
2	.003	-90.9	.010	-33.3	.011	-32.9	.021	365.4
2.1	.003	48.9	.003	30.6	.004	31.0	.008	401.2
2.2	.001	153.7	.009	-36.4	.012	-37.1	.029	74.8
2.3	.007	7.8	.014	31.4	.015	-45.9	.051	80.0
2.4	6.307	213.2	11.091	-65.0	9.161	-68.6	66.338	302.3
2.5	19.161	58.1	14.984	-189.0	18.277	-173.7	26.465	13.1
2.6	.057	22.2	.038	-345.4	.043	-352.0	.038	175.2
2.7	7.960	-103.5	3.722	-45.1	3.678	-36.4	8.896	250.7
2.8	.434	20.8	.059	12.2	.161	16.6	.331	487.8
2.9		144.7	18.611	-63.0	19.731	-52.3	5.726	110.5
3.0	.016	-129.9	.037	-330.1	.042	-320.6	.612	109.7
3.1	10.564	-88.9	3.064	-374.0	3.45	-366.5	5.061	-20.2
3.2	.021	-193.2	.059	-286.2	.023	-332.6	.133	119.9
3.3	.005	182.6	.046	192.5	.027	-7.9	.045	323.7
3.4	.103	84.7	.068	160.6	.054	-221.5	.056	336.6
3.5	.012	122.8	.010	146.8	.005	74.9	.022	463.1
3.6	.003	-80.8	.009	-317.8	.003	-412.7	.013	69.6
3.7	.015	-76.6	.039	-207.1	.016	-220.3	.036	347.7
3.8	.049	-135.1	.229	-299.2	.035	-322.3	.075	173.5
3.9	.058	100.1	.426	100.2	.064	-71.6	.180	394.7
4.0	.229	50.9	.703	-64.7	.091	-147.4	.191	161.3

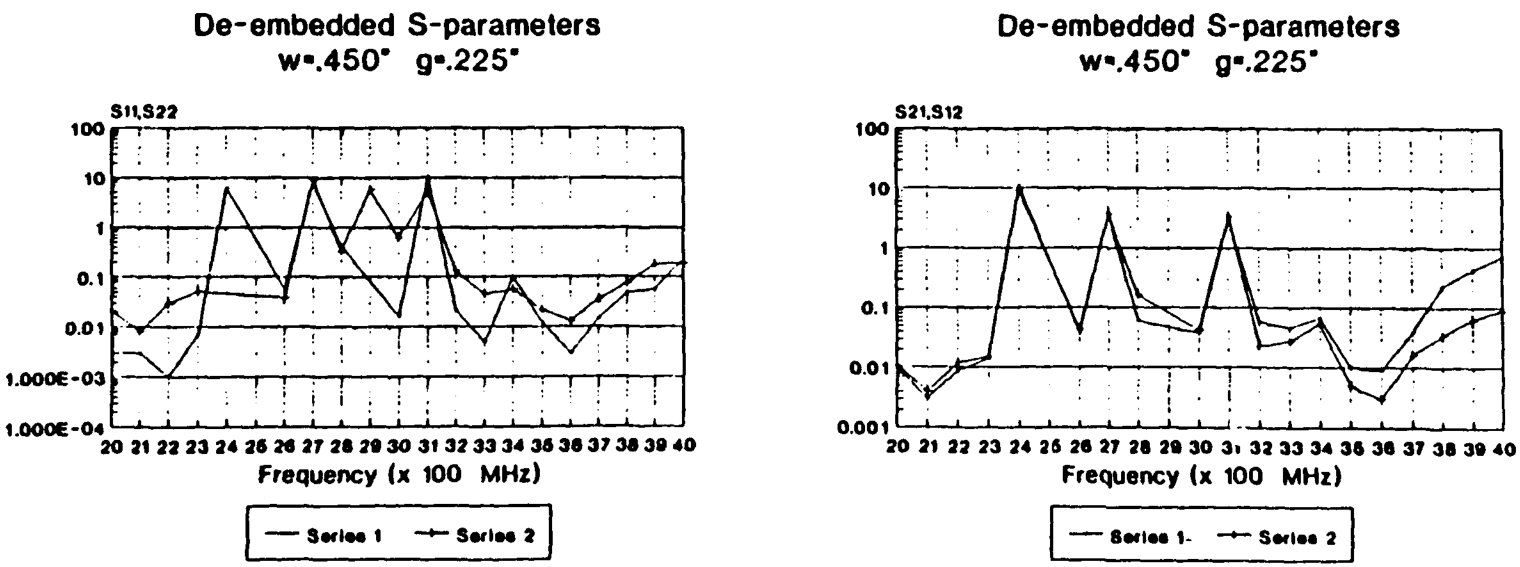
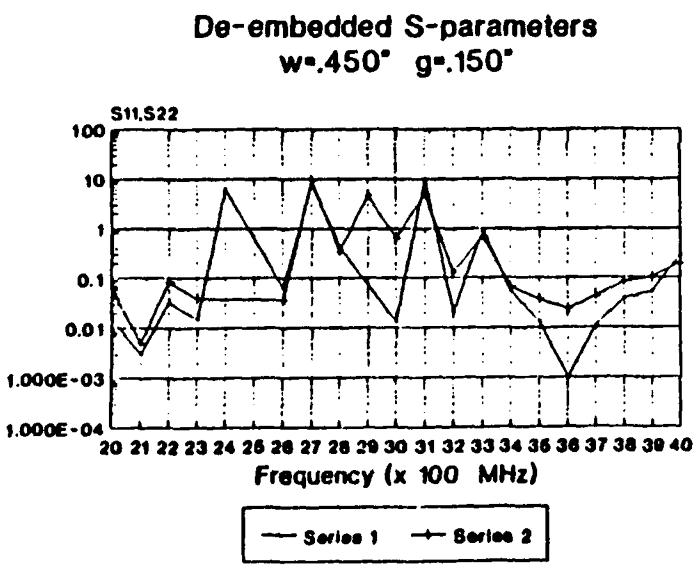


Figure 55. DE-EMBEDDED S-PARAMETERS

Table 29. DE-EMBEDDED S-PARAMETERS W= .450" G=.150"

Freq (GHz)	S11 dB	A11 °'s	S12 dB	A12 °'s	S21 dB	A21 °'s	S22 dB	A22 °'s
2	.016	-48.5	.035	-22.8	.037	-22.8	.065	362.0
2.1	.003	61.5	.002	38.5	.002	38.3	.005	408.1
2.2	.033	-66.4	.049	41.9	.061	41.6	.085	152.3
2.3	.015	2.3	.014	45.1	.016	39.2	.038	90.6
2.4	6.167	213.5	12.189	-63.5	10.854	-66.7	66.331	302.6
2.5	39.94	3.4	37.378	-199.5	42.581	-197.7	44.978	-26.1
2.6	.064	27.7	.049	-339.4	.052	-341.2	.036	168.4
2.7	8.179	-93.0	4.744	-41.3	4.617	-42.4	9.341	261.7
2.8	.432	20.9	.069	7.8	.071	7.4	.331	491.1
2.9	88.858	152.4	14.155	-24.8	14.909	-18.9	4.685	142.1
3.0	.013	-136.6	.047	-293.9	.052	-291.3	.634	111.0
3.1	10.098	-92.6	3.33	-370.4	3.794	-365.6	4.885	-19.2
3.2	.020	-279.1	.021	-376.8	.026	-389.6	.130	115.7
3.3	.907	8.5	.361	-330.2	.131	-330.0	.680	-8.0
3.4	.054	46.3	.019	-209.8	.022	-199.1	.068	357.3
3.5	.013	101.7	.009	98.0	.012	93.2	.037	470.6
3.6	.001	-135.1	.005	-352.0	.005	-363.6	.024	161.2
3.7	.011	-56.4	.018	210.3	.022	-191.4	.043	371.6
3.8	.038	-184.2	.037	-334.1	.042	-359.0	.083	144.3
3.9	.055	174.5	.069	-64.9	.068	-74.2	.108	373.0
4.0	.288	54.5	.098	-142.0	.118	-118.5	.197	151.9



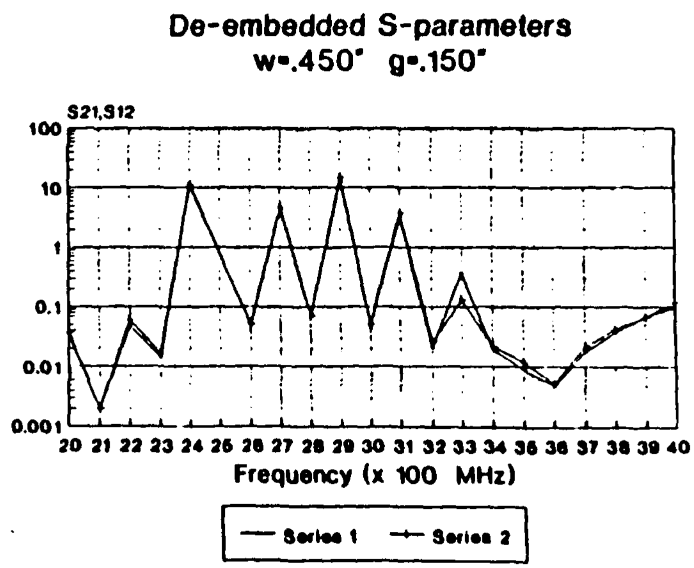
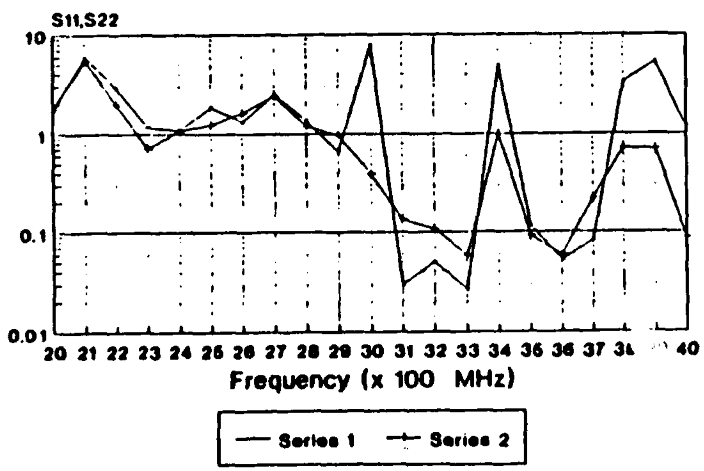


Figure 56. DE-EMBEDDED S-PARAMETERS

Table 30. DE-EMBEDDED S-PARAMETERS W= .300" G=.150"

Freq (GHz)	S11 dB	A11 °'s	S12 dB	A12 °'s	S21 dB	A21 °'s	S22 dB	A22 °'s
2	1.712	99.9	1.080	-190.6	.899	-180.1	1.813	120.4
2.1	5.936	-75.6	6.069	-441.2	3.994	-418.2	5.563	-78.5
2.2	2.950	-54.2	3.545	-225.5	1.144	-196.7	2.001	-43.6
2.3	1.169	93.6	1.349	122.5	.685	-74.9	.723	484.2
2.4	1.083	-200.6	3.207	-333.2	.602	-418.6	1.073	144.9
2.5	1.859	53.2	1.661	-47.1	1.265	-127.3	1.242	451.4
2.6	1.327	-41.4	.953	-186.7	1.020	-258.1	1.621	338
2.7	2.492	-236.9	2.550	-210.5	3.321	-268.3	2.423	113.5
2.8	1.350	-208.4	1.375	-194.5	2.204	-230.4	1.186	127.0
2.9	.661	-218.2	.712	-210.2	1.341	-225.1	.962	143.7
3.0	7.916	-21.1	3.121	-83.8	3.474	-86.0	.390	263.4
3.1	.030	-176.3	.211	-240.2	.274	-477.5	.134	221.7
3.2	.050	-11.4	.123	-215.9	.239	-270.8	.108	410.8
3.3	.027	-267.2	.024	-24.8	.714	-249.9	.058	93.4
3.4	4.836	-16.6	.556	46.9	2.690	-156.9	.994	324.6
3.5	.116	-137.5	.150	-38.2	1.129	-209.5	.092	134.3
3.6	.052	166.4	.040	-6.9	1.115	26.4	.059	113.6
3.7	.083	-185.1	.300	-340.6	.791	-297.0	.220	219.2
3.8	3.332	158.6	3.161	-57.8	2.487	-15.5	.717	486.3
3.9	5.304	121.8	13.641	-84.2	1.286	-57.1	.700	320.8
4.0	1.149	23.8	.709	45.5	.065	50.5	.088	314.2

De-embedded S-parameters
w=.300" g=.150"



De-embedded S-parameters
w=.300" g=.150"

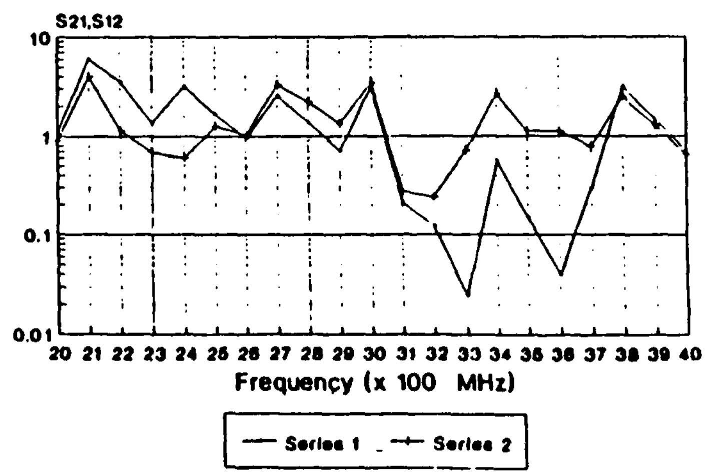
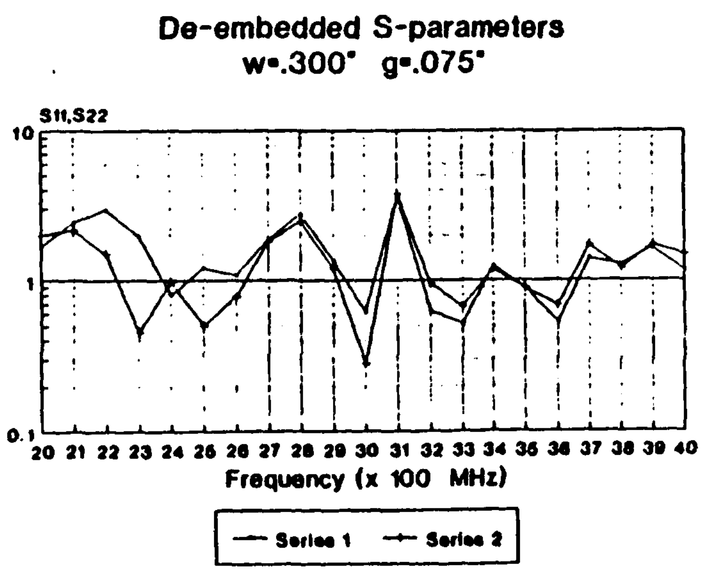


Figure 57. DE-EMBEDDED S-PARAMETERS

Table 31 DE-EMBEDDED S-PARAMETERS W= .300" G=.075"

Freq (GHz)	S11 dB	A11 °'s	S12 dB	A12 °'s	S21 dB	A21 °'s	S22 dB	A22 °'s
2	1.682	101.4	.914	4.2	1.191	12.4	2.006	144.7
2.1	2.450	272.5	1.243	71.4	1.453	-189.1	2.165	266.0
2.2	2.989	-100.4	1.346	-98.0	.966	-86.0	1.499	282.3
2.3	1.985	-269.0	.034	-357.0	.037	-311.2	.455	17.1
2.4	.802	86.1	1.262	-211.1	.542	-145.5	.985	420.1
2.5	1.212	23.1	.039	-250.2	.355	-276.4	.506	60.8
2.6	1.091	-8.5	.015	-495.9	.249	-428.9	.787	-10.2
2.7	1.870	299.1	.237	-22.5	.896	-34.0	1.816	305.5
2.8	2.785	-21.7	.810	14.2	1.472	-68.8	2.481	346.2
2.9	1.362	-58.2	.317	-51.7	1.103	-211.4	1.203	-55.7
3.0	.621	27.6	.481	278.1	.458	37.5	.282	332.9
3.1	3.690	-139.5	3.300	-253.9	5.863	-436.1	3.787	179.1
3.2	.628	19.4	.825	-213.2	.243	-338.0	.956	36.2
3.3	.517	139.2	.177	37.0	0	-169.6	.671	174.4
3.4	1.250	-20.3	.139	-231.2	0	-146.2	1.189	-15.7
3.5	.901	26.5	.450	-229.4	1.132	-207.1	.895	59.7
3.6	.530	12.1	.071	200.7	.537	-23.9	.686	36.0
3.7	1.404	65.3	.189	-93.7	.126	-41.9	1.722	439.8
3.8	1.271	79.3	.223	-53.9	.558	-99.0	1.202	98.2
3.9	1.645	44.4	2.403	-252.8	.557	-220.6	1.725	61.3
4.0	1.163	59.6	2.216	132.4	.222	48.2	1.491	399.6



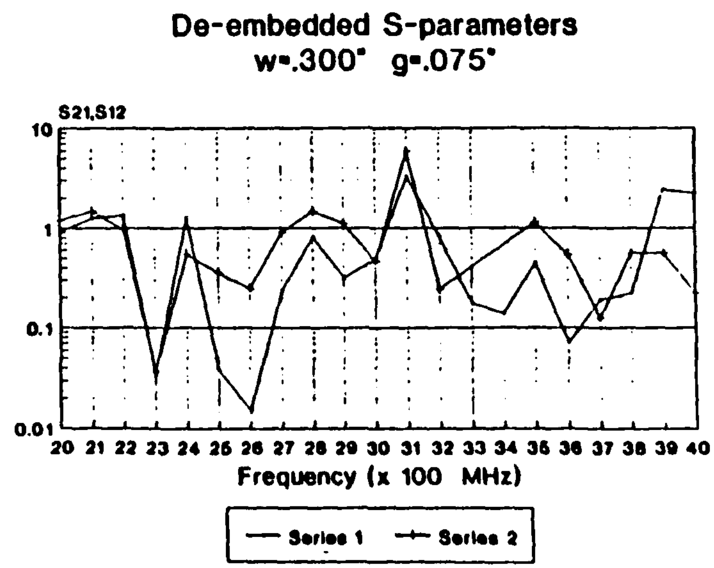
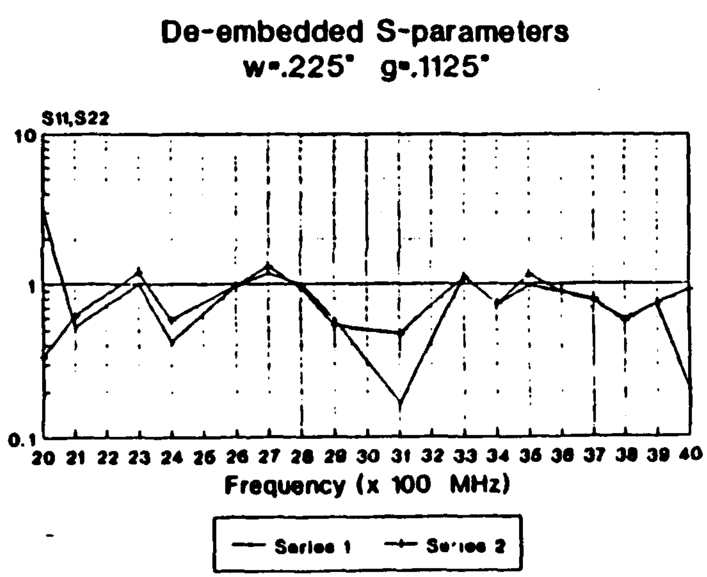


Figure 58. DE-EMBEDDED S-PARAMETERS

Table 32 DE-EMBEDDED S-PARAMETERS W= .225" G=.1125"

Freq (GHz)	S11 dB	A11 °'s	S12 dB	A12 °'s	S21 dB	A21 °'s	S22 dB	A22 °'s
2	3.166	295.2	.246	-190.4	.139	-197.5	.336	390.7
2.1	.525	194	1.106	-139.9	.698	-151.3	.621	168.0
2.2	30.99	29.3		-65.7	16.34	-77.2	73.09	442.3
2.3	1.002	-22.6	.371	0	.076	-14.9	1.204	358.6
2.4	.421	-23.4	.170	-296.7	.026	-323.0	.583	-32.8
2.5		-103.6		107.1	15.939	-146.6		268.7
2.6	.982	24.8	.013	36.0	.021	28.7	.981	384.9
2.7	1.177	-20.9	.765	-272.0	.542	-273.3	1.311	-61.0
2.8	1.001	-331.1	.018	-394.0	.010	-397.6	.947	32.1
2.9	.592	20.1	.086	-327.9	.030	-333.3	.538	316.1
3.0	14.87	122.7	38.289	-48.4	10.45	-54.3	30.635	69.3
3.1	.166	-254.3	.108	-424.5	.034	-431.4	.471	170.7
3.2	8.837	236.9	20.09	-158.8	7.282	-168.2	23.558	199.8
3.3	1.131	-26.7	.178	-230.7	.126	-242.6	1.117	331.7
3.4	.743	326.0	1.397	57.5	.011	-169.0	.743	325.1
3.5	.975	-21.0	.805	-.7	.022	-264.2	1.149	337.2
3.6	.889	159.5	.403	-160.1	0	-166.7	.894	157.8
3.7	.772	-39.4	.582	-279.5	.006	-209.4	.790	320.9
3.8	.587	23.5	.112	-85.7	.007	-124.6	.569	24.1
3.9	.742	-48.3	.094	-29.7	.152	-116.1	.752	308.5
4.0	.202	-236.4	1.698	-162.5	.195	-226.6	.910	75.4



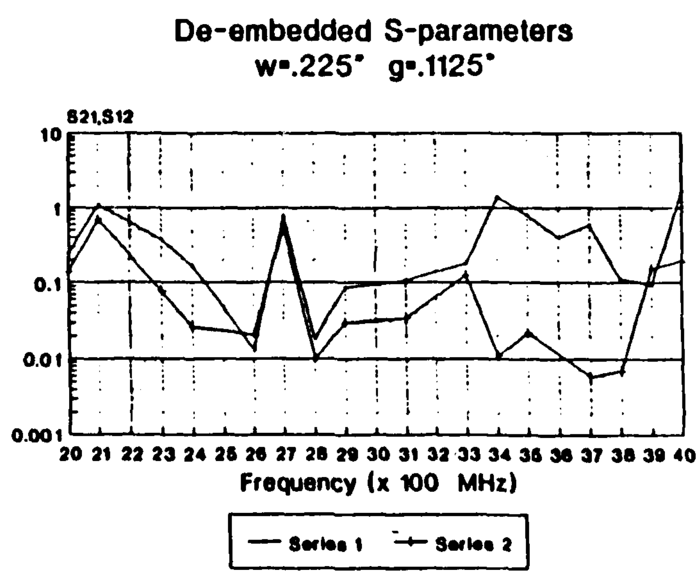


Figure 59. DE-EMBEDDED S-PARAMETERS

Table 33 DE-EMBEDDED S-PARAMETERS W= .225" G=.075"

Freq (GHz)	S11 dB	A11 °'s	S12 dB	A12 °'s	S21 dB	A21 °'s	S22 dB	A22 °'s
2	.485	27.7	.170	-369	.182	-404	.329	5.7
2.1	2.712	91.9	1.563	-324	1.711	-332	2.827	82.3
2.2		90.4		-72.9	56.29	-77.2		442
2.3	.933	-18.7	.036	204.4	.015	10.1	.914	341.8
2.4	.430	337.0	.034	-87.5	.016	-90.6	.452	340.2
2.5		265.3		-21.9	26.102	-238		277.1
2.6	.976	24.7	.030	24.0	.028	20.5	.970	384.8
2.7	.958	-4.1	.069	-19.1	.062	-20.5	.927	358.7
2.8	1.008	29.0	.018	-87.7	.012	-90.1	1.024	390.8
2.9	.584	20.0	.074	-330	.033	-334	.939	12.4
3.0	18.52	-120	60.85	-7.2	21.569	-119	3.26	96.5
3.1	.155	106.3	.033	-175	.014	-181.7	.172	458.9
3.2	24.65	-68.1	53.54	-454	26.928	-461.8	32.86	-122.0
3.3	.818	-25.1	.153	-409	.158	-417.8	.827	-21.6
3.4	.819	-28.3	.364	-420	.293	-460.5	.462	11.8
3.5	.983	-19.7	.253	-107	.186	-112.9	1.182	359.6
3.6	.898	159.3	.060	-272	.051	-276.1	.893	161.8
3.7	.762	-39.9	.074	-392	.080	-395.1	.721	-41.7
3.8	.588	23.6	.015	154	.015	-30.3	.579	25.1
3.9	.739	-48.1	.032	-322	.043	-288.9	.738	-46.0
4.0	.711	67.4	.568	20.9	.045	-144.7	1.046	66.1

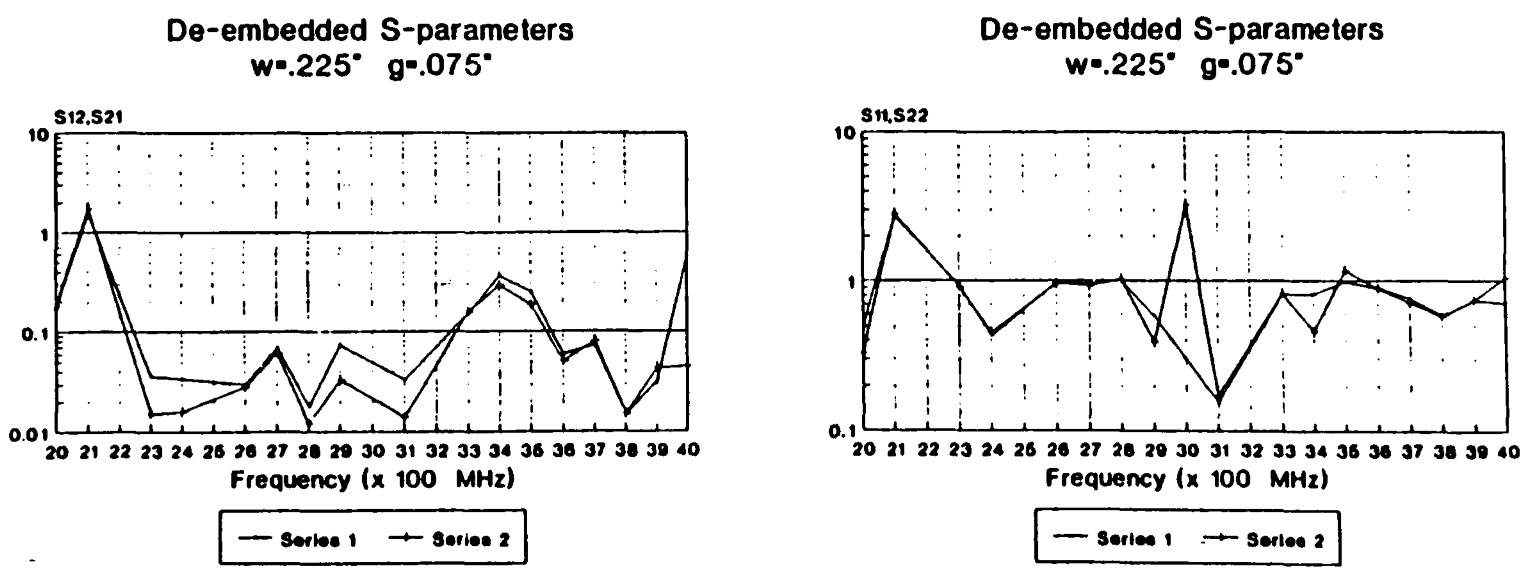


Figure 60. DE-EMBEDDED S-PARAMETERS

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